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DATA CORP MINNEAPOLIS MN 1986 N00014-78-C-0306

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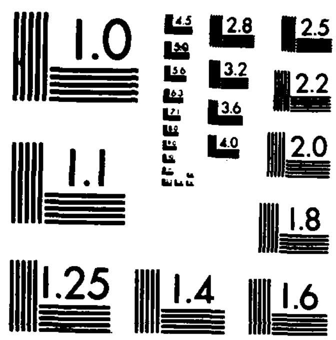

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SUBJECT: Final Report, Contract N00014-78-C-0306

This reports consists, mainly, of reprints of scientific papers prepared under this contract. Titles include:

During this contract the results were published as scientific papers as follows:

Nastrom, G. D. and A. D. Belmont, Evidence for a Solar Cycle Signal in Tropospheric Winds, Journal of Geophysical Research, Vol. 85, No. C1, pgs. 443-452, 1980.

Nastrom, G. D. and A. D. Belmont, Apparent Solar Cycle Influence on Long-Period Oscillations in Stratospheric Zonal Wind Speed; and Geophysical Research Letters, Vol. 7, No. 6, pgs. 457-460, 1980.

Belmont, A. D., Proposed Mechanism to Explain a Semi-annual Variation in the Winds in the Polar Mesosphere. ONR Workshop on Solar-Terrestrial Weather Relationship, Pgs. 159-163, 1981.

Corrections and comments on related subject included

Venne, D. E., G. D. Nastrom, and A. D. Belmont, Corrections to "Preliminary Results on 27-day Solar Rotation Variation in Stratospheric Zonal Winds". Geophysical Research Letters, Vol. 9, No. 7, pgs. 759-760, 1982.

Venne, D. E., G. D. Nastrom, and A. D. Belmont, Comment on "Evidence for a Solar Cycle Signal in Tropospheric Winds". Journal of Geophysical Research, Vol. 88, No. C15, pgs. 11,025-11,030, 1983.

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Evidence for a Solar Cycle Signal in Tropospheric Winds

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Amplitudes and phases of the 11-year solar cycle in wind speed and temperature at radiosonde levels have been determined. These results are based on 174 stations over the northern hemisphere for the 25-year data period 1949–1973. Amplitudes and phases were estimated by the method of time-lagged correlation with the quasi-periodic 10.7-cm solar radio flux. The largest atmospheric amplitudes are near the tropopause level during winter, where in several regions over 40% of the interannual variance of the wind speeds is explained by the solar cycle. The hemispheric patterns of amplitude and phase suggest that the year-to-year latitudinal oscillations of the jet stream and the amplitude of the major standing long waves both appear to vary with the solar cycle. It is suggested that these results are due to changes in ultraviolet radiation, causing changes in ozone, and thus in stratospheric temperature, height, and wind fields. These changes may influence long-wave vertical propagation characteristics and the direct radiation exchange between the stratosphere and troposphere. Possible problems with this hypothesis are discussed. To verify this hypothesis, the morphology of the solar cycle changes in stratospheric wind and temperature and the associated effect on tropospheric standing waves must be estimated. These results show that atmospheric responses to the solar cycle vary with longitude as well as with latitude. Hence studies of the atmospheric solar cycle must avoid arbitrarily combining stations over broad geographical areas or as zonal means.

INTRODUCTION

Year-to-year fluctuations in the general circulation of the atmosphere have a significant impact on human activities through weather changes, and understanding such interannual fluctuations is a goal of many long-range forecasting efforts. Because of the possible influence of changes in solar activity on the atmospheric circulation, and presumably because the level of solar activity is quasi-periodic, many studies have sought to determine correlations between meteorological and solar variables. A bibliography of many such studies has recently been prepared by *Shapley et al.* [1979], although *Pittock* [1978] points out that some of the results are of tenuous significance and some of the results appear contradictory. The development of a hypothesis for a physical mechanism could provide a useful framework within which to interpret the statistically significant results, and *Siscoe* [1978] has reviewed several suggested mechanisms. As regular upper air sounding programs did not begin until the 1940's, most studies of the solar cycle in meteorological variables have used data taken at the surface. However, dynamical processes act throughout the atmosphere, and clues regarding physical mechanisms may be more easily detected above the planetary boundary layer. For example, *Schwentek* [1971] found a correlation between sunspot numbers and 10-mbar temperatures over Berlin, and Figure 1*a* shows equally impressive correlations between wind speeds at 300 mbar at Oakland and Washington and the 10.7-cm solar radio flux. But correlations at single locations or for small regions usually have little significance, especially for suggesting physical mechanisms. Solar influences can be expected to affect the entire earth, although nodal regions may exist, and solar-terrestrial studies should search for such large-scale, not local, effects. One approach for elucidating any physical mechanism, if one exists, is to examine the degree of spatial and temporal correlation of the individual station data over the globe or a hemisphere. *Naujokat* [1978] has reported a hemispheric-scale variation in 30-mbar heights between epochs of increasing solar activity (1964–1969) and decreasing solar activity (1959–1964, 1969–1975). In the troposphere, *Brown and John* [1979] have studied the variations in 500-mbar wind speed over the North Atlantic for the period 1945–1975. No studies of the solar cycle in the upper troposphere on a hemispheric scale could be found.

The purpose of this paper is to present one example of the hemispheric-scale morphology of the atmospheric response at radiosonde levels to the solar cycle. Results are given for the time-lagged correlation patterns between seasonal mean zonal and meridional winds from 25 years of hemispheric radiosonde data with the seasonal variations of solar 10.7-cm radio flux. The patterns found are briefly discussed within the framework of suggested physical mechanisms.

DATA

Radiosonde data used in this study are for 174 northern hemisphere stations with over 13 years of data during the period 1949–1973, inclusive. All radiosonde data were obtained on magnetic tape from the World Data Center (WDC-A) Asheville; in monthly mean form for 1949–1962 and as individual daily observations for 1963–1973. The latter data were checked for hydrostatic consistency and then averaged into monthly mean form. In the early data set, only temperature and zonal and meridional wind speeds were on hand, so the analysis here is limited to these three variables. Station locations are shown in Figure 2. More stations, especially over the oceans, would be desirable, but these 174 are all that were available. A complete station list and details concerning the data are available upon request.

For each station, at each level, data were averaged to make time series of seasonal means, with winter being December–February. If less than five observations were available for any month during a season, the seasonal value was considered missing.

The number of available years of data for the winter season is given in Table 1. In general, stations operated by U.S. or British Commonwealth agencies have data at all radiosonde levels, and the data are usually distributed evenly over the entire period of record. Data from other available stations usually begin in 1956 and usually extend only to 100 mbar prior to 1963. A total of 38 additional stations with 5–13 years of

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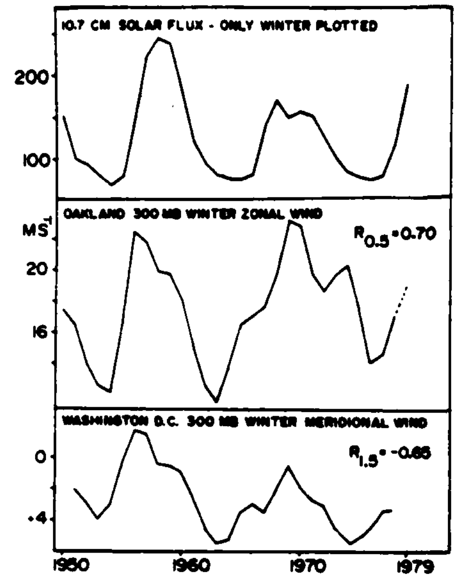

Fig. 1*a*. Comparison of long-period changes in solar flux and winter wind speeds at two stations. The subscript of the correlation coefficient R is the lag, in years, at which maximum correlation of the unsmoothed wind data with solar flux was found. Wind data in this figure have been smoothed with a $\frac{1}{4}$-$\frac{1}{2}$-$\frac{1}{4}$ filter. Note wind scale inverted on lowest panel.

Fig. 2*a*. Amplitude (meters per second) of the interannual zonal wind variation during winter at 300 mbar associated with the solar cycle and defined in the text. Stations where results exceed the 95% statistical confidence level are given by solid circles, and other stations are shown by open circles.

data at 300 mbar were used to estimate the seasonal mean wind fields discussed below. Wind data for 1974–1978 at 300 mbar, used in Figure 1 only, were taken from *Monthly Climatic Data for the World* [*NOAA*, 1974–1978], and wind data at 30,000 feet at Oakland, for 1979 (the dashed line in Figure 1), were obtained from WDC-A, Asheville.

Daily values of the 10.7-cm solar flux (adjusted to 1 AU) from 1947–1979, obtained from the World Data Center, Boulder, were averaged over individual 3-month seasons to form a single 30-year time series. An extract of this time series, showing the winters only, 1950–1979, is given in Figure 1. The standard deviation of daily solar flux within each season and the seasonal mean sunspot number were also used as other solar variability indicators, but these results were no more significant than the results obtained by using the mean solar flux and will not be discussed further.

The 10.7-cm solar flux is used here merely as an indicator of the level of solar activity. The solar emissions actually affecting the atmosphere (solar protons, ultraviolet radiation, precipitating electrons during enhanced geomagnetic activity, and others have been suggested) are not necessarily known. However, as reviewed by *Herman and Goldberg* [1978], the 10.7-cm flux correlates well with other solar variables both on the 11-year and on shorter time scales. In the seasonally averaged solar data used here, the 11-year cycle is definitely the dominant component of the variance, as can be seen by in-

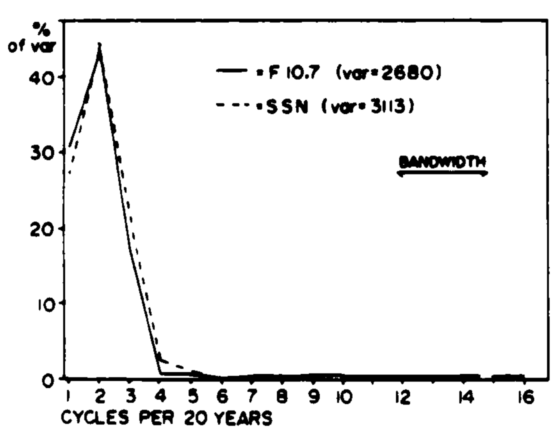

Fig. 1*b*. Variance power spectrum, smoothed by a Hamming filter, of the seasonal means of the 10.7-cm solar flux, 1949–1973. For comparison the spectrum of sun spot numbers is also given.

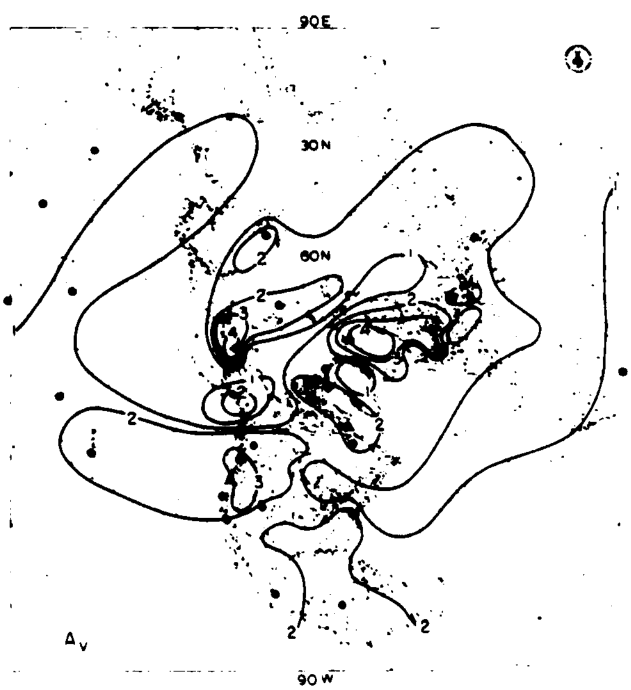

Fig. 2*b*. Same as in Figure 2*a*, except for meridional wind.

TABLE 1. Number of Available Stations by Length of Record

Area*	Level, mbar	Number of Stations <13 years	13–15 years	16–18 years	19–21 years	22–25 years
North America	700	5	2	17	15	27
	300	5	3	16	15	27
	20	31	16	15	4	0
Pacific and Japan	700	3	3	5	5	12
	300	3	3	6	4	12
	20	11	6	8	3	0
Europe, Asia, and Africa	700	30	16	55	3	4
	300	30	19	52	3	4
	20	101	3	3	0	1

*The total stations for North America are 66; for the Pacific and Japan, 28; and for Europe, Asia, and Africa, 108.

spection of the upper time series in Figure 1*a* or from the variance power spectrum in Figure 1*b*. The units of the 10.7-cm solar flux are 10^{-22} W m^{-2} Hz^{-1}.

METHODS AND RESULTS

The level of solar activity varies with an approximately 11-year cycle, and it is often assumed that meteorological variations are coupled with solar activity if they also show an 11-year cycle. Although it has no physical basis, this assumption will be used here. A different assumption, not used here, is that random atmospheric motions give the impression of an 11-year cycle [*Khromov*, 1973]. Convenient parameters for describing the spatial morphology of any periodic or quasi-periodic variation are the amplitude and phase of the variation, such as harmonic analysis results. However, routine harmonic analysis, where data are decomposed into sinusoidal variations, is not suited for use here. The solar cycle is not truly periodic (Figure 1) but varies in amplitude and period, and the analysis method used must reflect corresponding amplitude and period changes in the meteorological data (or lack of corresponding changes). Thus amplitudes and phases were determined by analogy with harmonic analysis methods, as is described next.

In harmonic analysis the customary way to find amplitude and phase is from the correlation of the data with sine and cosine waves, and the phase thus found is relative to the time $t = 0$. The percent of the variance of the data explained (PEV) by a given harmonic wave is

$$\mathrm{PEV} = A_t^2/2\sigma^2 \quad (1)$$

where A_t is the amplitude of the wave and σ^2 is the variance of the data (see, for example, *Panofsky and Brier* [1965]). It can easily be shown that exactly the same amplitude and phase are obtained if the lagged cross-correlation function between a cosine wave and the data is determined and if the phase is taken as that lag L, where the maximum absolute correlation coefficient is found. The phase is relative to the time when the cosine function is 1 (i.e., $t = 0$). The amplitude is given by

$$A = (2r_L{}^2\sigma^2)^{1/2} \quad (2)$$

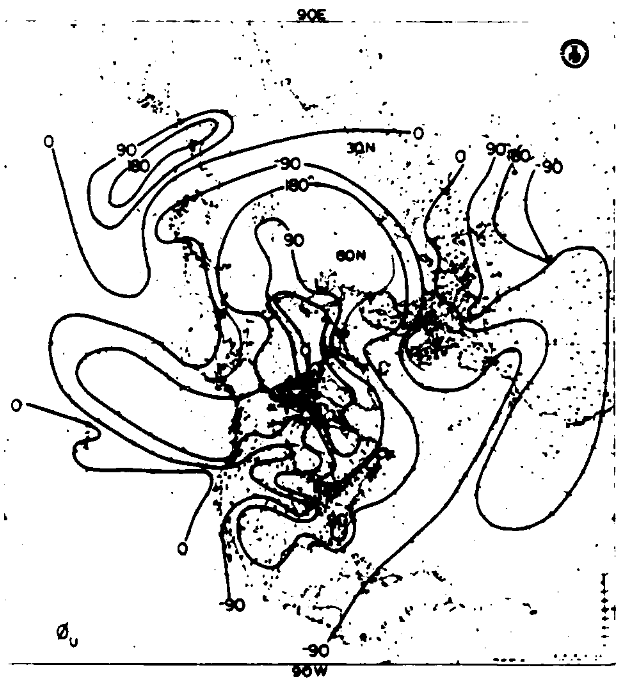

Fig. 3*a*. Phase of 300-mbar zonal wind (time of maximum eastward speed, given in degrees for an 11-year wave) relative to the time of maximum solar flux, during winter from time-lagged correlation analysis. Positive phase indicates solar maximum occurs before wind maximum. Dotted lines show some intermediate isochrones.

Fig. 3*b*. Same as in Figure 3*a*, except for meridional (northward) wind.

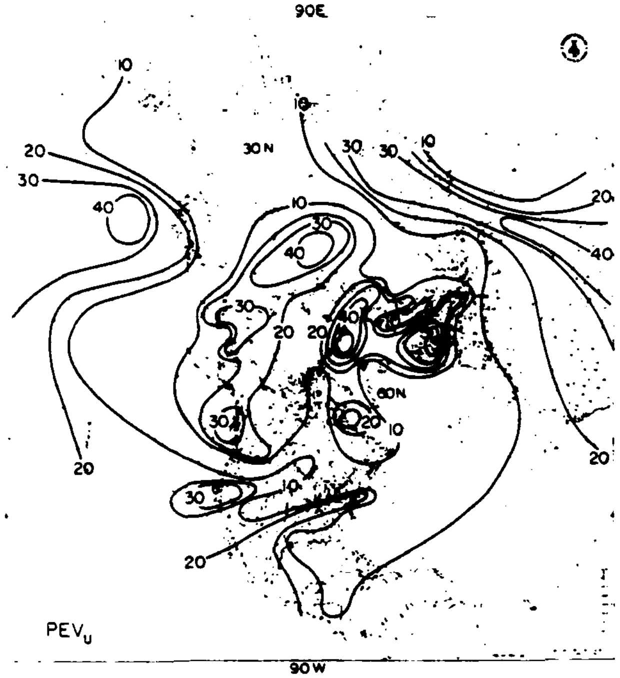

Fig. 4a. Percent of explained variance (PEV) due to correlation of zonal wind speed at 300 mbar during winter with solar flux. Note that PEV = r^2 thus where PEV = 40%, r = 0.63.

where r_L is the correlation coefficient at lag L. Note that this view of harmonic analysis permits an alternative way of showing the well-known fact that the percent of the variance explained by the correlation of one data set with another is r^2, because (1) and (2) yield

$$\text{PEV} = A^2/2\sigma^2 = r^2 \tag{3}$$

In this study the lagged cross-correlation function was determined by using the quasi-periodic solar flux, rather than an 11-year cosine wave. The phases thus define the time of the maximum in the meteorological variable relative to the time of solar maximum, and a positive phase indicates the solar maximum occurs before the meteorological maximum. If the absolute maximum of the cross-correlation function occurred at a negative value for any meteorological time series (e.g., the data in the lowest panel in Figure 1), one-half of a solar cycle, 5.5 years, was added to the phase so that all phase values refer to the time of algebraic maximum in the meteorological data.

To remove the large annual or semiannual variations from the meteorological data and to study the possible seasonal dependence of any meteorological-solar cycle relationship, the cross correlation analysis was made for each of the four seasons separately. For example, the correlation coefficient of the 25 winter temperatures at a given station and level with the 25 corresponding years' winter solar flux values is defined as lag 0, and the correlation coefficient of these same winter temperatures with the 25 preceding years' autumn solar flux values is called lag 1.

The analysis was made for each station, level, season, and meteorological variable, and only a selection of the results can be presented here, to illustrate the findings. Winter wind speeds at 300 mbar were chosen for preparation on maps because they generally show the closest relationship with the solar cycle (in terms of PEV), and maps of the temperature results at 500 mbar will also be given to support the discussion. Results at other levels generally follow those at 300 mbar but with reduced amplitude and some phase shift, as will be illustrated with meridional sections along three longitudes.

The patterns of amplitude and phase for the zonal and meridional wind speeds at 300 mbar during winter are given in Figures 2 and 3, and Figure 4 shows the PEV. The stations used are depicted by open circles in Figure 2, except that those stations whose correlation coefficient exceeded the 95% a priori confidence level are shown by dots. For the statistical confidence test the number of degrees of freedom was taken to be the number of data pairs actually present adjusted by the autocorrelation of the wind and of solar flux at lag 1 year, as prescribed by *Mitchell et al.* [1966]. For the solar flux, and at most stations where the correlation coefficient was significant, the autocorrelation function (for this relatively brief period of record) displayed the exponential-type decay described by Mitchell et al. At a few stations, however, the autocorrelation of the wind was negative, in which case the number of data pairs minus 2 was used. Even at the last stations, visual inspection of the time series of data indicates the large correlations are not because of one or two wild numbers but rather that the negative autocorrelation at lag 1 year is because of large year-to-year changes superimposed on a regular long-period variation. No a posteriori tests of statistical significance were made, as the true significance is perhaps best judged by the organization of the results over the hemisphere and from level to level.

When the correlation of two independent series is determined, one would expect the result to be above the 95% confidence level 5% of the time. In the present results 12% (21 stations) of the zonal wind values and 19% (34 stations) of the meridional wind values exceed the 95% level. While this is more than expected by chance, the significance of these percentages may be ambiguous due to an uncertainty in the number of truly independent stations present.

A stronger case for significance will be made by showing that there are consistent, continuous patterns of atmospheric response among the stations and that these patterns are linked

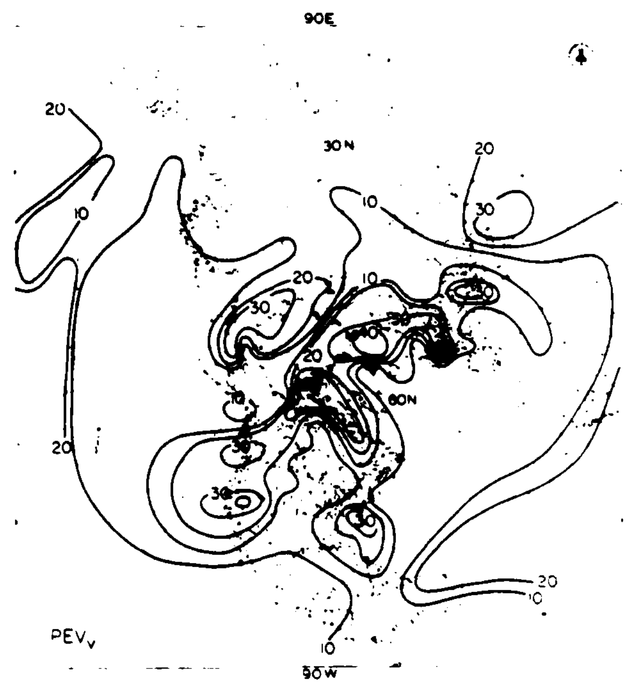

Fig. 4b. Same as in Figure 4a, except for meridional wind.

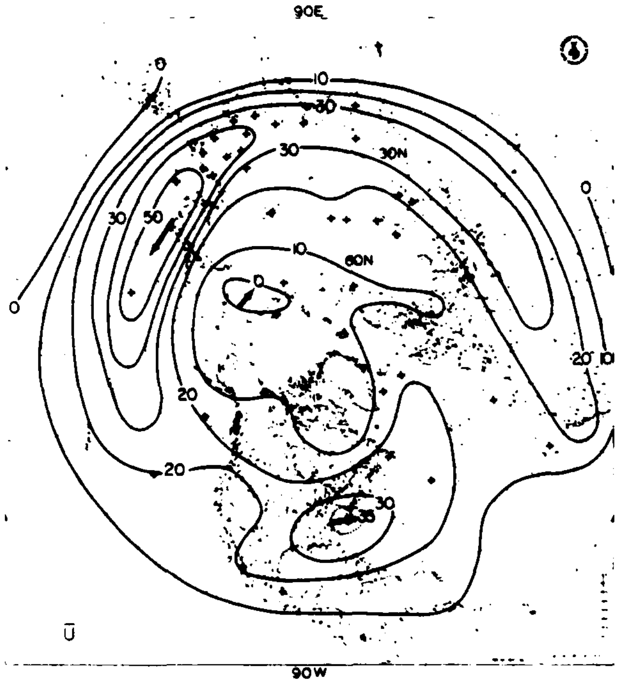

Fig. 5a. Winter seasonal mean wind speed (meters per second) at 300 mbar for zonal wind. Arrows show direction of flow. The 38 stations with 5–12 years of record, used here but not in other figures, are shown by small crosses.

with clearly identified features of the mean circulation. First, to aid in interpretating the patterns in Figures 2 and 4, the winter mean zonal and meridional wind speeds at 300 mbar are given in Figure 5. All available stations with over 5 years of data were used in preparing these mean charts, and the stations used here, but not in previous figures, are depicted by crosses in Figure 5*a*. The means given in Figure 5 closely resemble those given by others [e.g., *Crutcher*, 1959].

The amplitude of the zonal wind response, Figure 2*a*, is organized into several cells of large values separated by regions where the amplitude sometimes is very small. North of about 30°N, these cells can all be related to changes in the strength or position of the jet stream or of a standing wave. By comparing Figures 2a with Figures 3a and 5a, it is shown that the two centers of large amplitude along the west coast of North America, the two centers of large amplitude north and south of Scandinavia, and the two centers of large amplitude east of Japan are in each case located on opposite sides of the jet stream axis and are in each case about 180° (i.e., 5.5 years) out of phase. Variations with altitude at stations near these three meridians (125°W, 20°E and 140°E) are shown in Figure 6. In each case largest amplitudes are centered near the tropopause level north and south of the winter mean jet stream axis. Further, at the jet axis the amplitude is a minimum, and the phase changes relatively rapidly with latitude, leading to a 180° phase shift across the jet axis. Patterns of amplitude and phase such as these in Figure 6 could result from a latitudinal oscillation of the jet stream, north and south of its mean location, with the changing solar activity. This is in fact the case as is shown by the difference data in Figure 7. During the 3 years of low solar activity (1963–1965) the tropospheric zonal wind speeds along 125°W are greater near 55°N but are less near 40°N than during years of high solar activity (1957–1959 and 1968–1970).

A fourth pair of amplitude maxima is found over central Asia, near 70°E. The two centers of large amplitude near 40°N and 55°N are about 180° out of phase, as in the above three cases. In this case, however, the jet core is located south of both stations, unless there is a secondary jet not detected by the sparse station coverage available here. Alternatively, it may be that the center near 55°N is influenced by the changes in the standing wave trough over Siberia discussed next. This trough can be recognized from isotach patterns of meridional winds in Figure 5*b*.

In the Lake Baikal region the phases of the zonal and meridional components of the wind, relative to solar flux maximum, are near 90° and 0, respectively, while over northeastern Siberia the corresponding phases are near 180° and 90°. The deviations of the wind associated with the changing solar flux thus change from cyclonic to anticyclonic curvature in 180° (5.5 years), or in other words, the trough over Siberia deepens and fills with the changing solar flux. Over northeastern Siberia about one-third of the variance of both wind components is explained by correlation with the solar flux (Figure 4).

The trough over northeastern Canada apparently also changes with the changing solar flux. Only Frobisher (64°N, 68°W) shows amplitude above 3 m s^{-1} in the zonal wind speed, but there is a large region around Baffin Island where the amplitude of the meridional component (Figure 2*b*) exceeds 2 m s^{-1} and where over one-third of the variance is explained (Figure 4*b*).

The region of relatively large amplitudes over the southeastern United States (Figure 2*a*) is apparently due largely to the waxing and waning of the strength of the jet stream there. All stations with amplitude above 2 m s^{-1} show nearly the same phase, except Columbia, Missouri. Along an arc from Oklahoma City to Nantucket the phase is 150°. The phase at Nashville is a little earlier, while that at Columbia is much later so that Nashville and Columbia are 180° out of phase. As will be shown later in Figure 10, it seems that the jet stream over this area changes magnitude everywhere with the

Fig. 5b. Same as in Figure 5a, except for meridional wind.

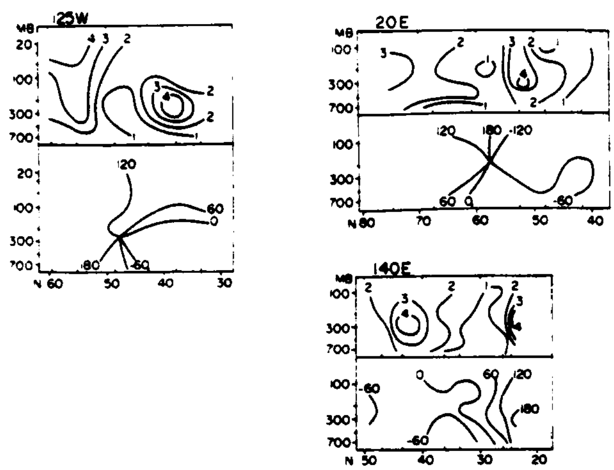

Fig. 6. Amplitude (meters per second, defined in the text) and phase of zonal wind variations associated with the solar cycle, as a function of latitude and height at three longitudes. Stations used in each chart are shown by upward pointing ticks. Above 100 mbar, sufficient data were available for this analysis only over North America.

changing solar flux and also shifts position north or south of Kentucky at the same time. However, other stations will have to be analyzed to decide if this is the reason why Columbia's phase is different.

The regions of large amplitude south of about 30°N in Figure 2*a* are intriguing but difficult to diagnose. Those over northern Africa are located near a jet core, but those over Hawaii and Mexico are far removed from a jet. The last may be associated with movements of the subtropical highs in response to solar activity, but until more stations become available the presence of large amplitude centers there seems to be an open question.

The wind variations shown above imply variations in the mean tropospheric temperature field at levels below 300 mbar. This expectation is verified by the 500-mbar temperature phase and amplitude (recall $A = (2r^2\sigma_T^2)^{1/2}$) given in Figure 8. The 500-mb level was selected for presentation because it is near the midpoint in altitude between the surface and 300 mbar. Of course, the amplitudes and phases of temperature vary with altitude, so only the gross features can be checked for qualitative consistency and only insofar as the 500-mbar level represents mean conditions between the surface and 300 mbar. For example, comparing temperature with zonal wind variations shows that the three pairs of large wind amplitude considered in Figure 6 each have an associated region of large temperature amplitude in Figure 8. Also, the phases of the wind variations are about +90° or −90° removed from the phases of the temperature variations, depending on whether they are north or south of the temperature maximum. The meridional wind has, for example, regions of large amplitude over Baffin Island and southern Alaska, which are 180° out of phase, separated by a region of large temperature amplitude over the Canadian Rockies, which is in phase quadrature with the meridional wind maxima. Other examples could be given, and counterexamples can be found which could be resolved only by examining the temperature variations at all levels, but in general the expected relationship between temperature and wind variations is verified.

DISCUSSION

Percent of Explained Variance

The amplitudes shown in Figure 2 are determined by two factors, the correlation coefficient and the variance of the wind. A comparison of Figure 4 with Figure 2 shows that the largest amplitudes of the solar cycle wind variation usually are associated with areas of its largest PEV. This association persists at other altitudes as shown by, for example, comparison of the meridional section of PEV at stations along the west coast of North America in Figure 9 with the amplitudes in Figure 2*a*, especially from 30°–50°N. Thus on a broad scale the amplitude varies more closely with changes in the correlation coefficient rather than by changes in the variance of the wind. On a regional scale, however, changes in the correlation coefficient and the variance of the wind both sometimes contribute to amplitude changes. For example, Table 2 lists three stations over western North America, their seasonal mean wind speed variances, PEV's, and the residual variances after correlation with the solar flux. Although the total variance changes very much among stations, the residual is nearly the same at all three stations. From these data it seems as if there is a background level of variance at each station (the residuals), and superimposed on the background is a component of variance related to the changing solar flux cycle. However, other factors must also influence the variance of the wind, because the pattern in Table 2 holds only in cases where the PEV is very large.

The important point here is that near the tropopause level in some areas as much as 50% of the year-to-year variance of the mean wind speed is associated with the cycle of changing solar flux and that north of 30°N all centers of large PEV are associated with large-scale features of the general circulation.

Statistical Significance

Two cycles of data at a single station would hardly be sufficient to establish the significance of any relationship, but 20 cycles probably would be sufficient. Then the question is: Are two cycles at 10 stations sufficient? Certainly, more than 10 stations (Figure 2) widely separated on the globe exceed the 95% a priori confidence limit for the zonal and meridional winds. But perhaps more importantly, there is a consistent pattern among the stations, and every amplitude maximum of the 11-year wave in wind, north of 30°N (Figure 2), is associated with a feature of the general circulation. Further, from the meridional sections (Figure 6), the phase and amplitude have well-defined patterns from level-to-level as well as from station-to-station.

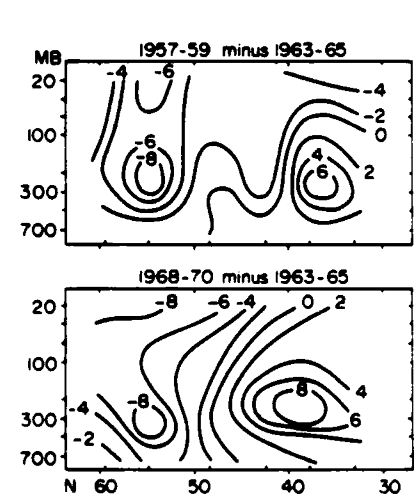

Fig. 7. Difference in winter mean zonal wind speed (meters per second) at stations near 125°W between years of high solar activity (1957–1959 and 1968–1970) and years of low solar activity (1963–1965).

Fig. 8a. Temperature variations (degrees Kelvin) at 500 mbar during winter associated with the solar cycle. The dots depict stations where results exceed the 95% confidence level.

Thus it is concluded that during the period 1949–1973 the winter seasonal mean wind speeds were significantly correlated with the changing solar flux, especially near the tropopause level and near jet streams or standing waves. Whether such correlations can be expected to persist is unknown, but the data in Figure 1 suggest they do persist. If a viable physical mechanism for these correlations were known, they would be of great value for understanding year-to-year changes in the circulation.

Physical Mechanism

In the troposphere the observed mean patterns can be viewed as the resultant of adding various standing planetary waves. For example, in Figure 5a around latitude 30°N the large jet maximum near 140°E and the smaller one near 80°W can be thought of as the sum of zonal waves 1 and 2. Around 60°N there are three alternate maxima and minima of varying strength, so contributions from waves 1, 2, and 3 could be expected. The point is that the observed pattern can change if any or all of the component waves change in amplitude or phase.

Stationary planetary waves are generated in the troposphere, largely by topography and nonuniform heating, and propagate upward into the stratosphere. For well-known reasons, only the longest waves (i.e., those with zonal wave numbers 1 and 2, and perhaps 3 and 4) propagate far above the tropopause and do so primarily during winter. *Bates* [1977] has shown theoretically that tropospheric stationary waves are very sensitive to changes in the stratospheric wind profile and static stability. Depending on the profiles of wind and static stability in the stratosphere, waves are reflected or transmitted in varying amounts. The amount reflected eventually determines the amplitude and phase of each stationary wave; and hence the sum of the individual waves, which is the mean pattern actually observed in the troposphere.

Hines [1974] pointed out that changes in the upper atmosphere could be manifested in the troposphere through planetary wave refraction. There is a growing body of evidence that mean stratospheric temperature fields, and hence wind fields, are influenced by solar changes [e.g. *Quiroz*, 1979; *Angell and Korshover*, 1978; *Zerefos and Crutzen*, 1975]. These variations may be linked with the changes in ozone suggested by observations to occur with solar changes [*Angell and Korshover*, 1976; *Blackshear and Tolson*, 1978] and now predicted by some photochemical models [*Penner and Chang*, 1978; *Callis et al*, 1979]. Thus it is suggested that the changes in tropospheric wind speeds found here could arise from small changes in the planetary wave structure, arising because of solar cycle changes in the stratospheric ozone and temperature and wind fields.

An alternative method whereby solar induced changes in the stratospheric ozone and temperature fields could interact with tropospheric long waves is by direct radiation exchange [*Ramanathan et al*, 1976; *Ramanathan and Dickinson*, 1979]. Planetary wave variations exist in upper stratospheric ozone and temperature [*Gille et al*, 1978], and if these waves vary with the solar cycle they could cause changes in the net heating patterns and resultant planetary waves in the troposphere. This would be especially important during winter when direct solar heating of the surface and hence lower troposphere is small or, at high latitudes, nonexistent.

The fact that most organized results at 300 mbar are found for the winter season is consistent with either of the above planetary wave mechanisms, because planetary waves are trapped below the stratospheric easterlies during the summer. Thus stratospheric propagation of waves, and radiation exchange, are of reduced importance during summer. Results for summer (not shown) are highly erratic, although over the western and eastern U.S. and over northern Europe the phases of the zonal wind speed do show a small degree of organization and (weakly) suggest a north and south oscillation of the jet stream, parallel to the winter results. While any response during summer seems to detract from a planetary wave mechanism, the possibility of interaction with the (winter) southern hemisphere circulation and the large thermal inertia

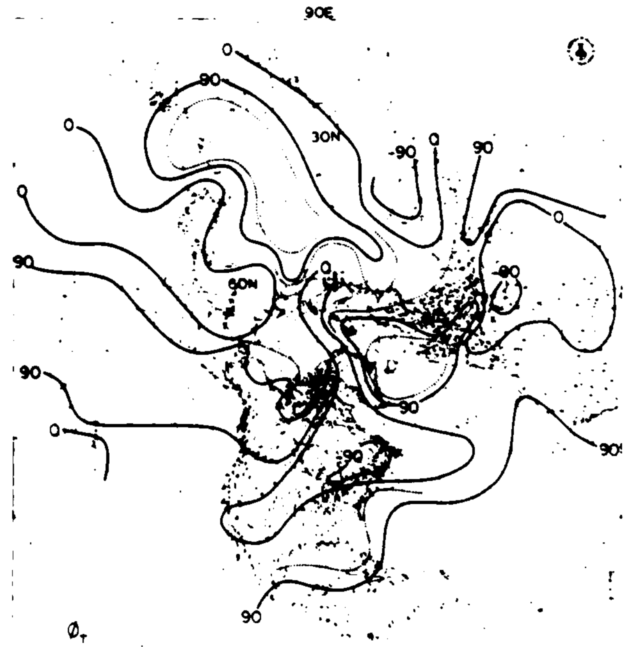

Fig. 8b. Same as in Figure 8a, except for phase.

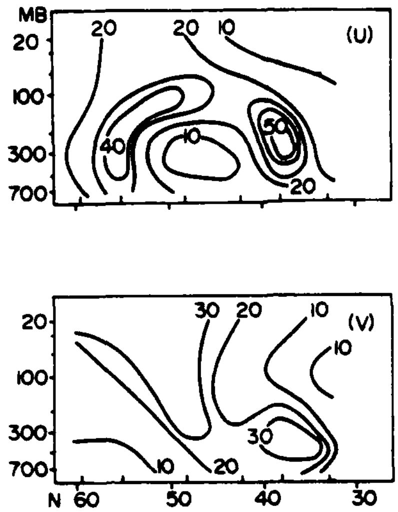

Fig. 9. Percent of explained variance due to correlation of winds at 300 mbar during winter at the same stations near 125°W used in Figure 6.

of ocean-atmosphere feedback processes should not be overlooked. Also, the possibility exists that other mechanisms, such as solar control of thunderstorms [*Markson*, 1978], may influence the summer circulation. The point here is that the most significant response is found in winter.

The presently available data provide no firm basis for accepting or rejecting either planetary wave mechanism hypothesis. To proceed further, the spatial morphology of the solar cycle variations of the mean winds, in addition to the temperatures, in the upper stratosphere must be defined. Also, to diagnose the relevant physical processes, quantitative models should be employed which incorporate interlevel feedback over the entire troposphere and stratosphere and which accommodate the dynamical-chemical interaction in the stratosphere arising from changing eddy fluxes of trace species because of changes in the planetary wave structure. Rocketsonde data at individual stations can be used to study the mean fields for the period 1960–1978, and satellite observations of the upper stratosphere, available after about 1970, should be useful for defining changes in the eddy fluxes and the wave structure of the upper stratosphere.

Practical Significance

To examine changes in the wind field associated with the solar cycle, the mean wind fields over the United States and Canada have been prepared for periods of solar maximum and solar minimum, using the amplitudes and phases in Figures 2 and 3, and are given in Figure 10. Detectable differences between solar maximum and solar minimum appear, especially over the Vancouver Island area and central Canada. Observed changes of the zonal wind speed over the former region were shown in profile form in Figure 7. In Figure 10*a* Vancouver Island is on the back side of a ridge (i.e., the winds are southwesterly), while the front side of the ridge (taken to be the 300° isogonic) is over extreme northern Saskatchewan. In Figure 10*b* all of western Canada and the western U.S. is on the leading side of a ridge (the winds are northwesterly) and the 300° isogonic is now over northern Manitoba. The trough over Hudson Bay is much sharper in Figure 10*b*. The axis of this trough over the United States, taken as the 270° isogonic, shifts from the New Jersey area westward to Detroit between solar maximum and solar minimum. The jet axis, which is split between the Ohio River valley and the Gulf Coast in Figure 10*a*, is continuous from southern Texas to Virginia in Figure 10*b*.

The possible influences on weather and climate of such small shifts in the location of major circulation features in the upper troposphere is not easily judged, although there is some evidence that surface storm frequency changes with the solar cycle [see *Herman and Goldberg*, 1978, p. 116]. Studies of baroclinic wave growth using numerical models [e.g., *Frederickson*, 1979] are just beginning to incorporate changes in the standing wave patterns, and their results are not yet suitable for use here. Experience indicates that the circulation at 300 mbar has some influence on surface weather, but many other factors not analyzed here, such as available moisture or atmosphere-ocean interaction, must also be considered.

The recent study by *Brown and John* [1979] indicates that surface storm tracks over northern Europe change with the solar cycle and gives evidence that these changes are related to changes in the 500-mbar zonal relative vorticity. Their results show that the largest vorticity changes over northern Europe at 500-mbar occur near 60°N. The present results in Figure 5*b*, obtained by an independent analysis method, show rapid phase changes near 60°N with large amplitude north and south of 60°N near 500 mbar and thus confirm and expand their results. However, as Brown and John point out, even the relation between surface storm tracks and surface weather is complicated and sometimes ambiguous.

SUMMARY

To determine the spatial morphology of tropospheric circulation changes with the solar cycle, the method of lagged correlation with the solar 10.7-cm radio flux has been applied to seasonal mean wind speeds and temperatures at 174 stations over the northern hemisphere. The results have been interpreted as amplitudes and phases of changes in the wind speed and in the temperature with respect to solar flux changes. Only results for winter have been presented, as they show greater organization than other seasons' results. While the results at several stations exceed the 95% a priori confidence level, a more convincing case for statistical significance has been made in terms of the organization of the patterns of amplitude and phase.

Largest atmospheric responses are always found (north of

TABLE 2. Variance of Winter Seasonal Mean Zonal and Meridional Wind Speeds at 300 mbar for the Years 1949–1973, Percent of Explained Variance, and Residual Variance After Regression on an 11-year Solar Flux

			Zonal			Meridional		
Station	Latitude, °N	Longitude, °W	Variance, $m^2 s^{-2}$	PEV, percent	Residual, $m^2 s^{-2}$	Variance,	PEV, percent	Residual, $m^2 s^{-2}$
Rifle	39	109	14.2	21	11.1	5.8	22	4.5
Ely	39	115	17.0	32	11.5	10.9	54	5.0
Oakland	38	122	21.6	54	9.8	6.5	34	4.3

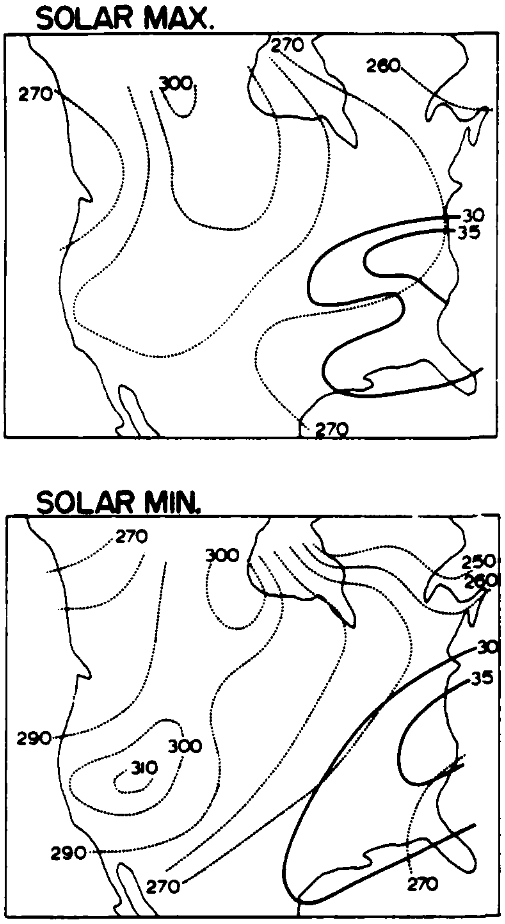

Fig. 10. Winter mean wind direction (degrees, dotted lines) and wind speed maximum over eastern United States (meters per second, solid lines) at 300 mbar for solar maximum and minimum. In the bottom chart the winds are more northerly over the western United States and more southerly over eastern Canada, and the jet stream is smoothly organized from Texas to Virginia.

30°N) near jet stream axes or standing waves. In several individual cases the jet stream axis appears to oscillate north and south of its mean position as solar activity changes, causing pairs of maxima in zonal wind speed amplitude, one on each side of the jet axis, and with opposite phase. At 300 mbar the ma[illegible] troughs, especially over Siberia and Canada, appear to wax and wane with changing solar activity.

It is suggested that changes in the structure of the standing planetary waves can account for the present results. Theoretically, the vertical propagation characteristics of planetary waves are sensitive to changes in the upper stratosphere, and there is a growing body of evidence, both observational and theoretical, that stratospheric circulation fields do change as solar activity changes. By varying the amount of reflection of upward propagating waves, these changes could lead to different resultant patterns in the troposphere. Also, changing the wave structure of the stratosphere can lead to changes in the radiant heat exchange between the stratosphere and troposphere, thus directly influencing the tropospheric planetary waves. Before this hypothesis can be accepted, it will be necessary to define the morphology of the solar cycle changes in the stratosphere and to determine the influence those changes could have on tropospheric planetary standing waves.

The net effect of the changes in the seasonal mean circulation at the tropopause level on surface weather cannot be assessed from these results alone. The patterns found here do suggest that future studies of meteorological variables should not arbitrarily combine stations according to latitude or over broad geographic regions. Further, the surface stations where large solar-weather effects are to be found (if any) may not be the same stations which have a large signal at 300 mbar. Finally, well-planned studies are needed of the solar cycle changes in stratospheric winds and temperatures, possible effects on the tropospheric standing waves, and the influence of changes in the standing wave structure on features which may influence the surface weather, such as storm development rate or propagation speed and direction.

Acknowledgment. This study was supported by the Office of Naval Research, contract N00014-78-C-0306.

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(Received May 10, 1979;
revised September 18, 1979;
accepted September 24, 1979.)

GEOPHYSICAL RESEARCH LETTERS, VOL. 7, NO. 6, PAGES 457-460, JUNE 1980

APPARENT SOLAR CYCLE INFLUENCE ON LONG-PERIOD OSCILLATIONS IN STRATOSPHERIC ZONAL WIND SPEED

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Abstract. The amplitude of the semiannual oscillation in stratospheric zonal wind speed, from rocketsonde data for 1960-1978, appears to vary as a function of the solar cycle. The apparent solar cycle modulation influence is present at all latitudes, and is largest near the stratopause. The amplitude of the semiannual wave decreases up to 50% at all latitudes from solar maximum to minimum. During 1950-1978, the period of the tropical quasi-biennial oscillation at 30 mb varied inversely with the solar cycle. These results indicate care must be taken to consider solar-cycle effects when comparing results for different periods of record or when estimating long-term trends.

Introduction

The equatorial center of the semiannual oscillation in zonal wind speed, located near 50 km and with maximum amplitude near 30 ms^{-1}, was identified about 15 years ago (Reed, 1966), but continues to defy complete theoretical description. Dunkerton (1979) reviews the observational and theoretical studies of the equatorial oscillation and presents numerical model results which reproduce several prominent features. He notes, however, that several features of the equatorial semiannual oscillation remain to be explained and are presently subjects of speculation.

Besides the familiar equatorial center, a second distinct center of the semiannual oscillation near 65 km at 55°N was reported by Groves (1972) and Belmont and Dartt (1973) as shown in Figure 1a. As it is located at 65 km, near the highest altitude reached by meteorological rockets, and below the altitudes usually sampled by meteor wind or radio reflection methods, the physical reality of the high latitude semiannual oscillation has been tenuous. As no previous observational study of it has used data beyond 1971, the first goal of this study was to update the earlier periodic analysis results by using data through 1978, and to verify the high latitude semiannual oscillation.

The new results (Figure 1b) show amplitudes of the semiannual wave are only 50% as large as those reported in Belmont and Dartt (1973) for the high latitude center, and the northward extent of the equatorial center (taken as the 20 ms^{-1} contour) is now only 22°N, rather than 30°N. (Phase patterns changed very little from the results of Belmont and Dartt, and so are not reproduced here.) These changes can hardly be attributed to poor sampling in the earlier (1960-1971) data set used by Belmont and Dartt because, although the number of observations has doubled with the added years of data, the stations between 20°N and 35°N and near 60°N had sufficient observations to yield very low amplitude errors in that analysis. It is suggested these changes may be due to solar cycle effects, and supporting evidence for the semiannual and quasibiennial oscillation (QBO) is given in the next section.

Rocketsonde data used here, summarized in Table 1, were obtained on magnetic tape from the World Data Center, Asheville, for 1960-1976. At those stations whose data extend beyond 1976, the winds at 40, 44, 50, 54, 60, and 64 km were taken from tabulations obtained from NASA, Wallops Station. For convenience, phase dates of the QBO were taken from the time-height section of Coy (1979).

Results

For the annual and semiannual waves, two separate analysis methods were used: first, the 12 monthly mean values for each individual year were analyzed by harmonic analysis. Linear interpolation was used to estimate any single missing monthly mean; if data for two consecutive months were missing, the year was not analyzed. This analysis resulted in a time series of yearly estimates of the semiannual and annual waves' amplitudes and phases at each station and level.

An example of these results is given in Figure 2 for the semiannual amplitudes at 40-64 km at White Sands, which had the longest and most complete set of data. (For the presentation in Figure 2 only, the time series has been densified by using overlapping 12 month periods centered six months apart.) Notice the resemblance between the changes in semiannual amplitude and in sun spot number (dashed line) especially at the highest levels. Correlation coefficients (r) at 52-60 km exceed the 95% a priori confidence limit. At other stations, r values are nearly all positive above 40 km.

For the correlation of the annual wave's amplitude with sun spot number, the r values are generally positive at high-latitude stations but are negative at mid-latitude stations, and have mixed signs at low-latitudes. Because of the small number of years of data (16 years maximum), little

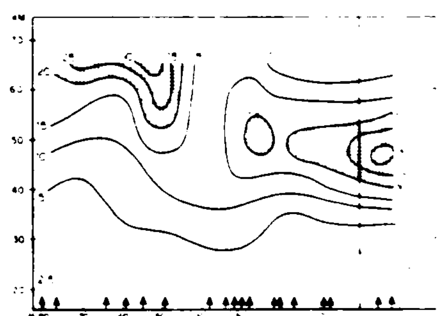

Fig. 1(a). Amplitude of the semiannual oscillation in zonal wind speed from rocketsonde data, 1960-1971, as given by Belmont and Dartt (1973). Arrows depict rocket station locations.

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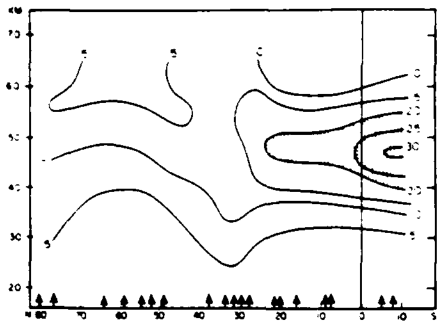

Fig. 1(b). As in Part (a), except for 1960-1976 (some data through 1978).

weight can be attached to the actual numerical values of r and it is noted only that the algebraic signs seem to have a pattern with latitude. This pattern of r values for the annual wave could arise from poor sampling, or from changes with solar activity in the position of the stratopause winter jet or in the phases of standing planetary waves, or for some other reason. As there is presently no way to decide this issue, the annual wave will not be considered further.

A second method of demonstrating that the semi-annual amplitudes vary during the solar cycle is to compute average values over years of high or low solar activity. An added benefit of this method is that it provides an objective estimate of the climatological bias incurred if the results from just one time period were assumed to be representative for all years. To apply this method, the basic period of record, 1961-1976, was divided into three parts according to solar activity: low (1961-1966), moderate (1967-1970), and low (1971-1976). In order to obtain error estimates, the periodic analysis technique used by Belmont and Dartt (1973) was applied for each time segment separately.

Results for this analysis are given in Table 2 at those altitudes near the maximum semiannual amplitude at each station (Figure 1). At all stations, except Churchill, the amplitudes of the semiannual wave are larger during 1967-1970 than during either period at low solar activity. At five stations, the estimate during 1967-1970 is larger than during other periods and the error bars do not overlap, which indicates with 95% confidence that the amplitudes are truly different. The effect of the solar cycle on these amplitude patterns is more easily seen in Figure 3. Note that the center panel most closely resembles the old results in Figure 1a and the bottom panel most closely resembles the new results in Figure 1b. This is because the frequency of observations was steadily increasing with time through 1976, and the data in Figure 1a (taken in 1960-1971) thus mainly reflect solar maximum, while those in Figure 1b (for 1960-1976) most strongly represent solar minimum.

The QBO is not truly periodic, but varies in period and amplitude from cycle to cycle. Also, even after the annual wave has been subtracted from the original observations, the durations of the consecutive easterlies and westerlies are not necessarily the same. Thus, the period of the QBO depends heavily on how one defines a cycle. One method is to define the period of time from the beginning of a westerly phase to the beginning of the next westerly phase, and Figure 4 compares a time series of QBO periods at 30 mb at 9°N, thus defined, with solar activity. The correlation at lag two years is remarkably high (-0.79) and is significant at the 99% level even after accounting for autocorrelation. However, it must be pointed out that lower correlations result if one uses

Table 1. Station list.

a. Stations used for all results

Station	Lat*	Lon*	Years of Data	N (at 50 km)
Greely/Poker Flats	64.0	145.7	1960-1976	1592
Churchill	58.8	93.8	1960-1976	1563
Primrose	54.8	110.1	1967-Apr 1979	855
Wallops	37.8	75.5	1960-1978	1992
Pt. Mugu	34.1	119.1	1960-1976	2571
WSMR	32.4	106.5	1960-1976	3361
Canaveral	28.5	80.5	1960-1976	2729
Barking Sands	21.9	159.6	1962-1976	1968
Antigua	17.1	61.8	1963-1976	794
Sherman	9.3	80.0	1966-1976	1115
Kwajalein	8.7	-167.7	1964,1969-1976	847
Ascension Island	-8.0	14.4	1963-1976	1679

b. Stations used only in Figure 1

Station	Lat*	Lon*	Years of Data	N (at 50 km)
Heiss	80.5	-58.0	1962-1970	162
Thule	76.6	68.8	1965-1976	589
Shemya	52.7	-174.1	1975-Apr 1979	168
Volgograd	48.7	-44.4	1965-'70,'72-Jun '78	473
Natal	-5.7	35.2	1966-1973	128

* N or W; minus is S or E.

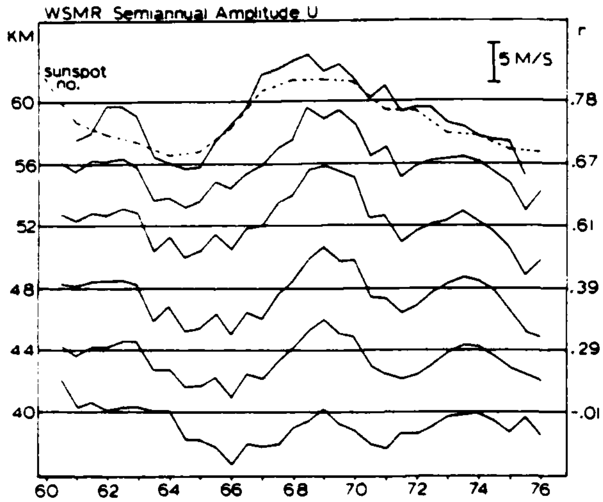

Fig. 2. Semiannual amplitudes for individual years at White Sands (32°N). Horizontal line at each level represents 15 ms^{-1} amplitude. Tick marks are for July 1 of each year. Amplitudes for the 12 months centered on January 1 are included in the curves here, but were not used when computing the correlations (r) with annual mean sun spot number given at the right.

other definitions of the QBO period as shown below:

Definition of QBO Period	Correlation	Lag(months)
west + east	-0.79	24
east + west	-0.53	12
duration of westerlies only	-0.59	14
duration of easterlies only	-0.55	12

These data strongly suggest that the period of the QBO is related to solar activity. This suggestion must be regarded as preliminary at this time, but if it is borne out by future data, it may be necessary to look for a solar mechanism for the modulation of the atmospheric QBO. As the solar cycle precedes the wind cycle in this correlation, and as the QBO occurs earlier at higher altitudes, this corresponds to an in-phase relation near 45 km which is the level of maximum amplitude of the equatorial semiannual wave. This suggests that the modulation of the QBO may be caused by the earlier modulation of the semiannual variation, and recalls an early theory of the equatorial QBO which linked its phase to the semiannual oscillation (Lindzen and Holton, 1968).

Discussion

The results presented here clearly illustrate that there are pronounced solar modulations of the periodic variations in the winds of the upper stratosphere. All users of stratospheric data should be sensitive to the period of record of their data and should be careful when comparing results based on different time segments. The systematic circulation changes seem to be related to the level of solar activity, although due to the relatively short data record available, this relationship must be considered preliminary.

The relationship between the semiannual wind amplitudes at mid- and high-latitude stations and sun spot number is consistent with, but does not prove, an hypothesis that this oscillation is influenced by ozone changes associated with magnetic storms (Belmont, et al, 1974a, b). Early results of an ongoing dynamical-chemical modelling effort (DeVore and Venkateswaran, 1977) indicated that the high-latitude semiannual oscillation is thermally forced and depends on both radiation and photochemistry. Thus, dissociation of N_2 or O_2 during geomagnetic storms, which have a strong semiannual component modulated by the solar cycle, or a solar-cycle variation in solar ultra-violet radiation, could lead to modulation of the semiannual changes in ozone and temperature and hence wind. Although there is some hint of a high-latitude semiannual oscillation in total ozone (Wilcox, et al, 1977; Hilsenrath, et al, 1979), a corresponding long-term observation series of

Table 2. Amplitude (m/s) of the semiannual wave in zonal wind speed for periods of low (1961-1966 and 1971-1976) and moderate (1967-1970) solar activity, at selected levels. Statistical error estimates (m/s) and number of observations are also given. Relative maxima are underlined.

Station	Altitude (km)	1961-1966 (solar minimum) AMP	Err	N	1967-1970 (solar maximum) AMP	Err	N	1971-1976 (solar minimum) AMP	Err	N
Greely	60	15.4	3.5	163	22.9	4.5	147	10.5	2.3	449
Churchill	60		M		15.3	6.2	114	17.0	2.3	702
Primrose	60		M		28.1	8.7	86	15.5	2.6	519
Wallops	60	13.5	8.0	121	18.0	7.0	161	11.4	3.4	553
Pt. Mugu	60	9.0	5.9	183	15.4	4.9	209	10.3	3.2	550
WSMR	60	11.4	3.1	655	20.2	2.8	679	12.6	2.3	1159
Pt. Mugu	50	12.1	2.3	801	16.9	2.2	803	13.4	2.1	967
WSMR	50	14.8	2.0	1094	18.0	2.0	922	13.6	1.8	1345
Canaveral	50	18.5	1.8	944	22.2	1.9	823	19.7	1.8	962
Barking Sands	50	17.2	2.8	359	25.0	2.0	679	20.0	1.7	932
Antigua	50	16.3	2.4	153	25.5	2.3	271	23.9	2.0	370
Kwajalein	50		M		24.9	3.0	176	21.8	1.4	654
Sherman	50		M		23.5	1.6	464	20.6	1.2	616
Ascension	50	25.7	1.9	398	30.5	1.7	642	26.5	1.6	639

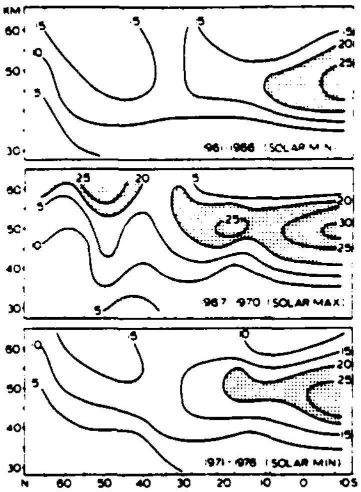

Fig. 3. As in Fig. 1, except for periods of solar activity minimum (1961-1966, 1971-1976) and maximum (1967-1970).

high altitude ozone is still not available and there is no present way directly to show the presence or absence of a semiannual component in the high-latitude high-altitude ozone field.

The "anomalous" effect at Churchill in Table 2 indicates that any physical relationship is not simple. It is well known that standing planetary waves exist in the upper stratosphere (except during summer) and the differing results at Churchill and Greely may thus merely reflect solar related changes in the planetary wave structure. On the other hand, there may be another explanation because Quiroz (1979), in his study of summer temperatures, also found an inverse relation between temperature changes at Greely and Churchill. As even fewer high-latitude rocket stations than used here are now available, this problem can only be resolved after more solar cycles of upper-stratospheric satellite measurements have been collected.

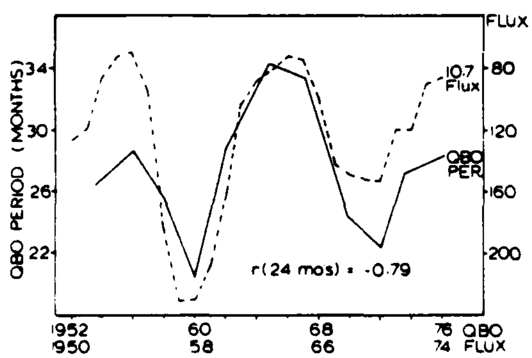

Fig. 4. QBO period at 30 mb at 9°N (measured from the beginning of one westerly phase to the beginning of the next westerly phase) compared with yearly mean solar activity.

Conclusions

1. The amplitude of the semiannual variation in zonal wind speed decreases from 10-50% from solar maximum to minimum.

2. The period of the QBO varies inversely with the solar cycle, and can have a correlation of -.8 at a lag of 24 months at 30 mb (24 km).

3. Care must be taken to consider solar-cycle effects when comparing results for different periods of record or when estimating long-term trends.

Acknowledgment. This study was supported by the Office of Naval Research under Contract N00014-78-C-0306. Presented at 17th IUGG Assembly, Dec. 7, 1979.

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(Received January 22, 1980;
accepted April 11, 1980.)

F m Proceedings of an ONR
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19 May 1981) Publ. by ONR,
Pasadena

PROPOSED MECHANISM TO EXPLAIN A SEMI-ANNUAL VARIATION IN THE WINDS IN THE POLAR MESOSPHERE

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As this is a meeting on proposed mechanisms of solar-terrestrial relations, I would like to review one hypothesis that was proposed to explain a property of the long-term variations of the stratospheric winds. This has been published, but may be of interest to those who are not familiar with it (Belmont and Dartt, 1973; Belmont et al. 1974a, 1974b).

Figure 1, shows the amplitude of the semi-annual variation of the wind, as a function of altitude and latitude. It has a normal tropical semi-annual variation which has been well-known since the middle 1960's. The arctic center at high latitudes and high altitudes is not yet well recognized. It extends up into the lower thermosphere but only the lower fringe of it can be seen here; it seems to be quite separate from the tropical one, both in phase and in amplitude distribution. It has its maximum at the equinoxes, but there is no explanation to date as to what causes it, except an hypothesis. The first reaction when this was published was that the semi-annual variation was not real, that it couldn't be; that it was just poor data because it was on the upper fringe of the reach of rocket data, and true, there weren't very many observations. This covered a period from 1960 to 1971. About 1978, the analysis was updated by consolidating all available data to produce Figure 2, in which the polar center was much reduced. There was a tendency to say our critics were right and that the initial version was simply due to poor data; there really was no polar semi-annual variation after all. However, the period of data that went into each analysis reflected, relatively, periods of solar maximum and solar minimum. The number of observations of rocket data increases in time, except since 1979 when it has decreased rapidly. But in these earlier years, each year's number of rocket observations was far greater than in previous years. So though the period of the first data group was 1960 to 1971, it reflected mainly the latest observations from the rather moderate solar maximum of 1969. When the data period was extended through 1976, the results really reflected solar minimum.

To check that, the data were separated according to solar minimum and solar maximum. In 1961 to 1966, during solar minimum, the amplitude is weak at high latitudes, but for the period 1967 to 1970 it is strong. And then, during the period of the most recent solar minimum, 1971 to 1976, it disappeared again (Figure 3, Nastrom and Belmont, 1980).

The checked rocket data are not available for several years after the observations are made, so the strength of the polar semi-annual variation during this last solar maximum, from 1978-80, cannot yet be verified.

Now the question is: "what causes it?" The hypothesis we advanced was suggested by the fact that the equinoctial phase of the semi-annual variation of the wind coincides with the equinoctial phase of the semi-annual variation of geomagnetic activity. Other things being equal, it seems reasonable to say that therefore there should be more geomagnetic storms and particle precipitation during the equinoxes, than at other times of the year. If that is acceptable, then that should lead to semi-annual disassociation of O_2 or N_2, and affect the formation of ozone at lower altitudes, thereby changing the heat distribution and the winds. This is now a hypothesis that others have also invoked. Hypotheses involving atmospheric chemistry at high levels are very hard to verify until estimated trace species concentrations, realistic reaction rates, absorption coefficients and radiation rates can all be confirmed. We are presently examining ozone profiles observed by Nimbus 4 to see if the semi-annual variation in ozone exists at these latitudes on a global scale. It was already found near 18 km over North America in ozonesonde data (Wilcox et al., 1977).

An eleven-year solar effect may be seen not only in the semi-annual variation, but also in the annual and the quasi-biennial variations. Figure 4 (Nastrom and Belmont, 1980) shows the period of the quasi-biennial oscillation on one scale and the 10.7 cm solar flux on an inverted scale; the correlation is reasonably good. They are out of phase, with a lag of about 24 months. This lag has its maximum at around 30 km, and if one extrapolates the QBO phase upward at the usual descent rate of the QBO of one kilometer per month, it would imply that the QBO would be in phase with the sun at near 50 km which is a region that might easily be affected by particles. Work is continuing by examining particle precipitation directly for evidence of semi-annual and QBO periods.

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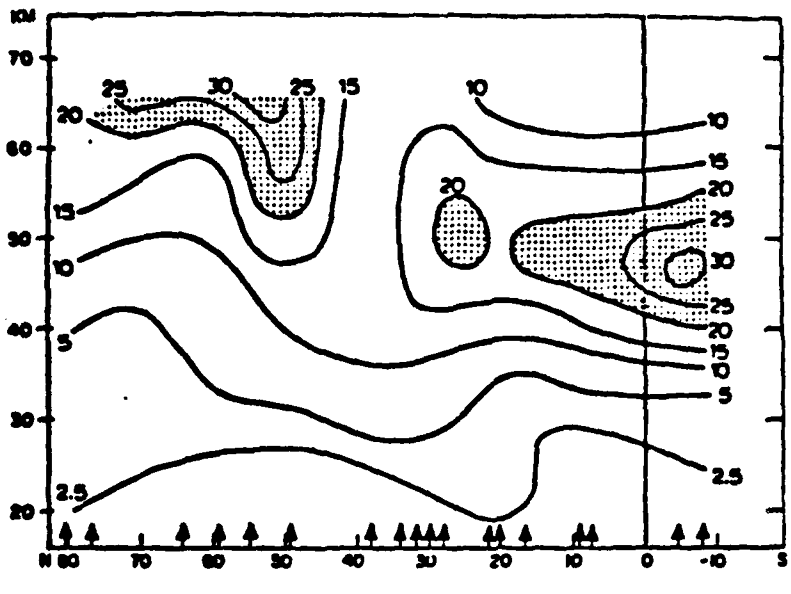

Figure 1. Amplitude of the semiannual oscillation in zonal wind speed from rocketsonde data, 1960-1971, as given by Belmont and Dartt (1973). Arrows depict rocket station locations.

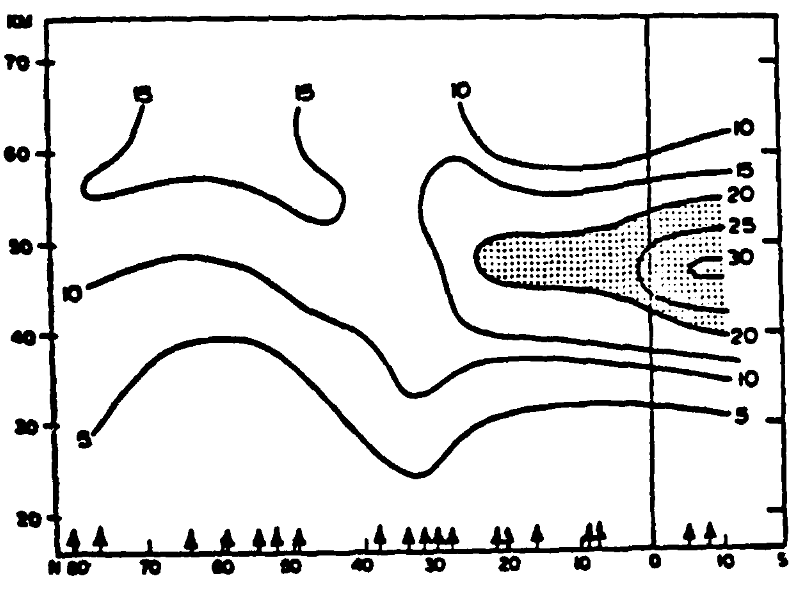

Figure 2. As in Figure 1., except for 1960-1976 (some data through 1978)

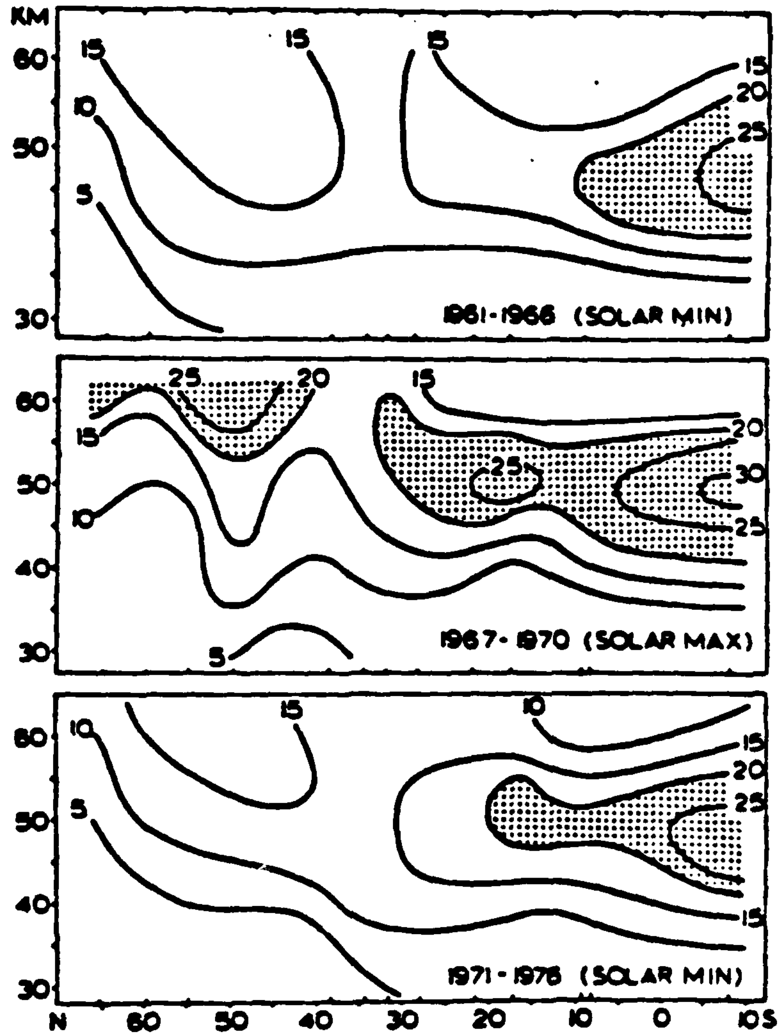

Figure 3. As in Figure 1., except for periods of solar activity minimum (1961-66, 1971-76) and maximum (1967-70)

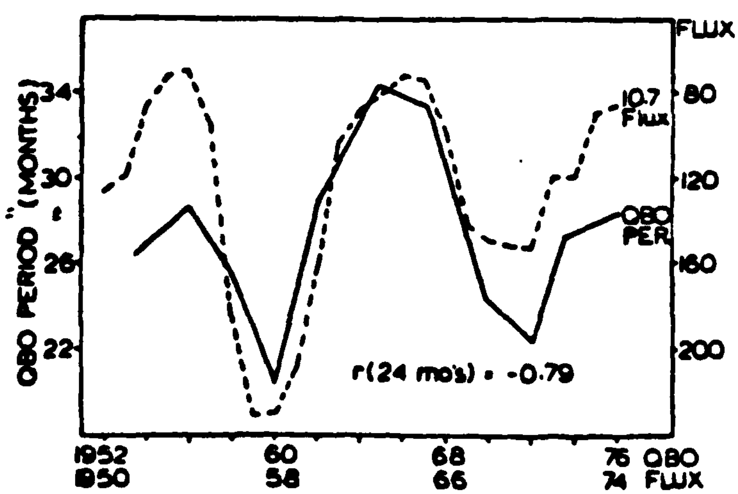

Figure 4. QBO period at 30 mb at 9° N (measured from the beginning of one westerly phase to the beginning of the next westerly phase) compared with yearly mean Solar activity.

CORRECTIONS TO "PRELIMINARY RESULTS ON 27-DAY SOLAR ROTATION VARIATION IN STRATOSPHERIC ZONAL WINDS" BY G. D. NASTROM AND A. D. BELMONT

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Introduction

In reviewing past articles on possible atmospheric variations induced by solar-cycle variations, it has been found that a contribution by Nastrom and Belmont (1978, hereafter denoted NB) incorrectly used statistical confidence limits to determine significance levels for coherence. This problem, along with a computer program error which caused the degrees of freedom to be overestimated, greatly affected their findings. The current note describes the correct procedure and the properly obtained results.

Methodology

The study by NB sought to describe variations in the stratosphere and lower mesosphere which could be related to the solar 27-day period variation. The data consisted of the 10.7 cm solar flux and rocketsonde wind and temperature measurements taken between 1960 and 1976. Thirteen rocketsonde stations were used, with data representing seven levels between 26 and 62 km altitude. Data measured within two-day intervals were averaged to yield bidaily values; no procedure was used to generate bidaily values for intervals which were without data. The bidaily values were filtered to remove variations of period greater than 90 days. The coherence between the solar and terrestrial variables was calculated using lag-spectral methods as described by Jenkins and Watts (1968). The 95% significance level K for the inverse hyperbolic tangent of the coherence was determined by the relation

$$K = 1.96/N^{(1/2)} \qquad (1)$$

where N is the degrees of freedom. This expression actually yields the 95% confidence limits when used according to Jenkins and Watts (1968). N is given by

$$N = 2.667 \cdot T/L, \qquad (2)$$

where T is the number of data pairs analyzed and L is the maximum lag, taken to be 61 by NB. The factor of 2.667 accounts for the use of a Tukey spectral window. T was chosen to be the number of data pairs at lag 1, as the number of pairs at lag 0 was much larger than at any other lag.

NB found that 19 out of 87 station-levels (21.8%) were 95% *a priori* significant when winter zonal winds were analyzed. The data were also divided into years during which the solar activity was low (1972-1976) and moderate (mid-1966 through mid-1971), and it was found that over 20 station-levels were at least 90% significant in both cases.

Paper number 2L0938.
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Corrections

The equation used by NB to determine the significance of coherence values was misapplied; it produced significance levels which were too easily satisfied. The true testing levels are giv-

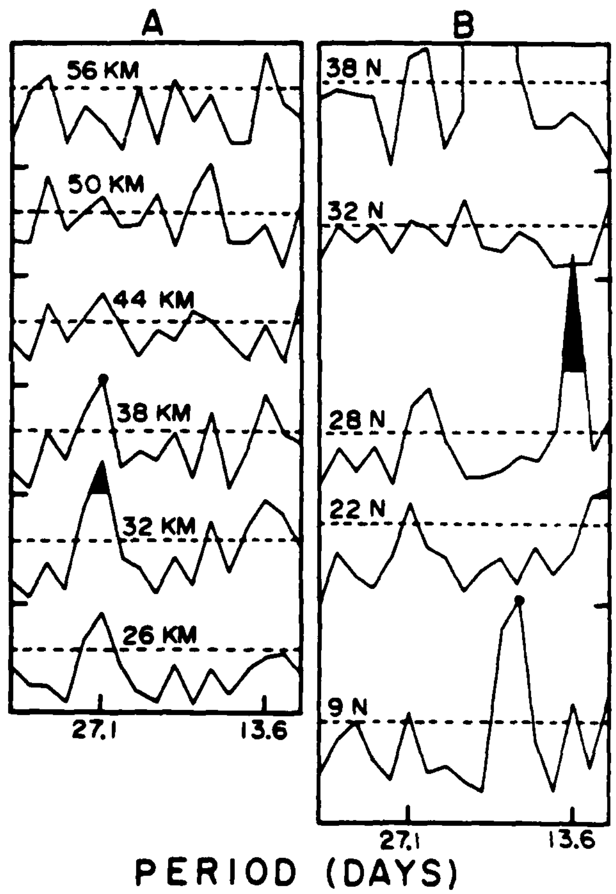

Fig. 1. The transformed coherence spectra between the winter zonal wind and 10.7 cm solar flux, corresponding to Fig. 1 of Nastrom and Belmont (1978) but with the corrections described in the text applied. Spectra are for data from (A) Churchill, and (B) altitude 56 km at various latitudes. The solid areas denote significances greater than 95% *a priori*; the dashed lines indicate the 95% levels used by Nastrom and Belmont. Blackened circles indicate values slightly above the corrected significance level. The discontinuity in the spectrum at 38°N latitude in (B) indicates spectral instability.

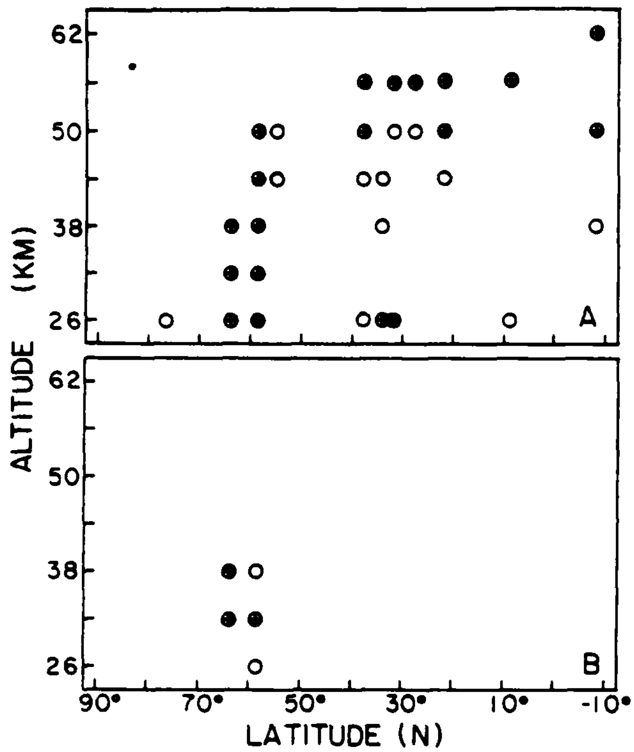

Fig. 2. Significance maps of the winter zonal wind and 10.7 cm solar flux at period 27.1 days (A) as given by Fig. 2 of Nastrom and Belmont (1978), and (B) after the corrections described in the text have been applied. Crossed and open circles denote station levels whose significance exceeds 95% and 90%, respectively.

en by the equation found in Panofsky and Brier (1958), Amos and Koopmans (1963), and many others. The 95% significance level for the coherence squared, CS_{95}, is given by

$$CS_{95} = 1 - 0.05^{1/((N/2)-1)} \tag{3}$$

where N is the number of degrees of freedom as defined previously. [The clarification of what is meant by degrees of freedom provided by Julian (1975) should be noted.] The distinction between the confidence limits and significance levels of coherence is mentioned by Halpern (1973).

As previously stated the text of NB indicates that the number of lag 1 data pairs was used to determine the significance levels. However, an error in the analysis computer program resulted in the use of the lag 0 numbers. This also had the effect of causing a substantial increase in the number of significant station-levels.

Two figures found in NB which are affected by the above errors are reproduced in their corrected form here. The coherence squared spectra of winter zonal wind at Churchill station (59°N latitude) and from several latitudes at 56 km altitude show a marked decrease in the number of significant peaks (Fig. 1). A significance map of the winter zonal winds at all station-levels (Fig. 2) indicates that only 3 of the possible 82 data series (3.6%) are 95% a priori significant at a period of 27.1 days; NB had formerly found 19 of 87 (21.8%). (Five station-levels are omitted in the reanalysis because they have less than 2 degrees of freedom.) In addition, the 22 of 82 station-levels found by NB to be at least 90% significant during low solar activity years decrease to 8 of 79 station-levels when the corrections are applied. The NB results for moderate solar activity years have been lost, but a similar decrease can be expected. It should be noted that the amplitudes of the zonal winds attributable to the solar 27-day variation reported by NB remain unchanged by these corrections. The interpretation of these amplitudes as representing a true sun-wind relationship is dubious, however, in light of the corrected significance tests. In addition, considerable spectral distortion is present due to the relatively large maximum lag. This distortion is greatest at periods less than ~20 days; its effect at 27-day period cannot be adequately assessed and therefore makes interpretation more difficult.

Summary

The findings of NB have been shown to be greatly changed by the correction of two errors. The new results indicate that any solar influence with period near 27 days in the data is at or below the level of detection in the present analysis.

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(Received April 20, 1982;
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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. C15, PAGES 11,025-11,030, DECEMBER 20, 1983

COMMENT ON "EVIDENCE FOR A SOLAR CYCLE SIGNAL IN TROPOSPHERIC WINDS" BY G. D. NASTROM AND A. D. BELMONT

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Abstract. In a previous paper it was suggested that a substantial 11-year period solar cycle influence may exist in tropospheric wind and temperature data. The current study reanalyzes a subset of the original data with the intent of better assessing the significance of the reported correlations. Extensive use is made of empirical testing; also employed is a maximum entropy spectral analysis. The new findings indicate that the correlations between the 10.7 cm solar flux and 300 mbar winter winds are not statistically significant. An upper limit on the percentage of variance in these winds explainable by a solar cycle influence is suggested to be ~8%.

1. Introduction

A previous article [Nastrom and Belmont, 1980 (herein denoted by NB)] explored the correlations between interannual variations in seasonal tropospheric meteorological variables and the 10.7-cm wavelength solar flux. The purpose of that study was to examine the morphology of solar-induced tropospheric variations having time scales similar to the solar cycle of ~11-year period. The findings in NB indicate that an average of ~20% (and at some locations as high as 50%) of the interannual variance in upper tropospheric winds and temperatures could be explained by the solar cycle. NB also reported the presence of large-scale, seemingly coherent patterns of correlation and phase between the solar and terrestrial data. The physical significance and interpretation of these features were also discussed in NB; however, the statistical significances of the results were determined through a priori testing and the use of arguments concerning the spatial coherence of the correlations. The a priori tests applied in NB were conceptually valid for harmonic analysis. Pure sine waves are correlated with data in harmonic analysis, and the length of the data set must be an integer multiple of the sine wave period. Because the solar flux did not form a true sine wave and the wind data sets used were of varying lengths, the testing methodology applied in NB greatly overestimated the significance of the correlations.

The purpose of this paper is to evaluate more thoroughly the statistical significance of the correlations reported in NB through further analysis of the original data. Owing to the relatively short period of available data (spanning about two solar cycles), it is not possible to use a rigid statistical criterion for the assessment of significance. Thus, extensive use is made of empirical methods employing random data and artificial solar cycles. This approach was suggested by A. B. Pittock (personal communication, 1980) shortly after the appearance of NB and is conceptually the same as that used by Quiroz [1981] in his study of solar effects on the QBO. The results of the tests presented here show that the true significance of the correlations is much less than NB estimated with a priori testing. Further, the consistent patterns of amplitude and phase among stations are not unique to the 11-year period but are found to occur at periods of 5, 8, 14, and 17 years as well.

The results found here provide an estimate of the upper bound on the magnitude of possible solar effects in the upper troposphere. A rough determination of this limit, applicable to the winds near 300 mbar, is obtained through several methods.

Paper number 3C0796.
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2. Data

NB found that the largest correlations were obtained when winter 300 mbar winds were compared with the solar flux; hence, this study employs only these winds. Of the 174 radiosonde stations considered, some were rejected by NB because of insufficient data; data from about 158 northern hemisphere stations were analyzed. Five of these stations had 13 years of recorded winter season wind data, and one had 12 years of data. The present study examines winds from 165 stations having 12 or more years of data; 6 stations are in the southern hemisphere. The average station length is 19 years. Only 28 stations have 15 or fewer years of record. Ambiguities concerning the number of stations previously used at 300 mbar have prompted the use of the slightly larger data set.

The solar data extend from 1947 to 1973; the radiosonde data series represent winds from 1950 to 1973. Each data series is composed of seasonal averages, for seasons defined as December-February (winter), March-May (spring), June-August (summer), and September-November (autumn).

3. Preliminary Analysis

This section describes the results of empirical tests made by using the same data analyzed in NB. These tests involve the use of fictitious wind data, which provide the percentages of stations with significant results and average percentage of explained variance (PEV), for comparison with those from observed data. Fictitious solar flux data, allowing random hemispheric patterns of PEV to be generated, are also used. All of the tests employ the same analysis technique utilized by NB, which is briefly outlined here. NB calculated the correlation coefficient r between the solar flux and wind series at 41 different lags, each lag being one season. The largest absolute r value was selected and tested for a priori significance. A t-test was used for this purpose, with the degrees of freedom

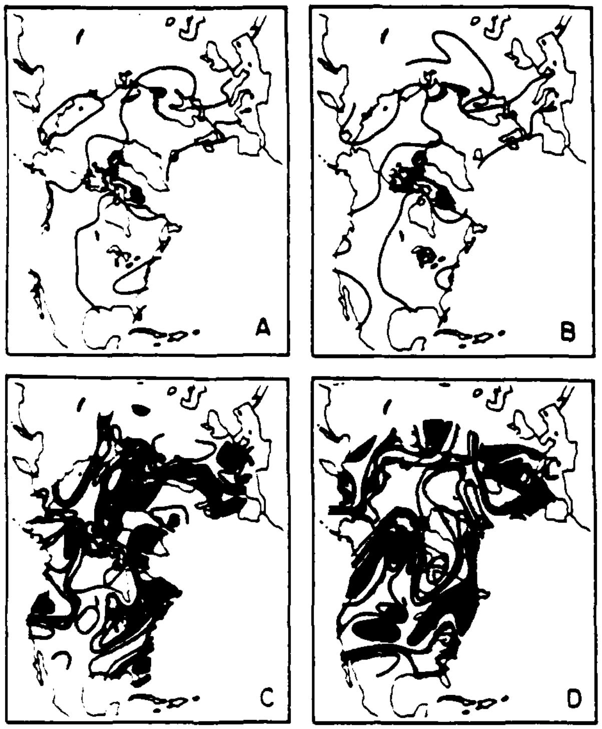

Fig. 1. The maximum percentage of explained variance (PEV) between (a) the 300 mbar winter meridional (v) wind and the 10.7 cm solar flux and (b) the v-wind and the fictitious flux of 11-year period. Areas of PEV greater than 20, 40, and 60 are indicated by the heavy line, stippling, and solid regions, respectively. Also depicted are the lags at which the maximum PEV's occur between (c) the v-wind and the 10.7 cm solar flux and (d) v-wind and the fictitious flux of 11-year period. Lags of 0-2, 4-6, and 8-10 years are represented by solid, heavily stippled, and lightly stippled areas, respectively. In all cases, only areas of sufficient station contiguity are contoured.

(DOF) determined from the number of data pairs at the lag selected. The DOF were further adjusted to account for autocorrelation; it should be noted that this adjustment was of questionable effectiveness in this case. The PEV was set equal to $100r^2$. Some minor changes have been made for the present study that result in an increase in the number of significant stations. These changes include using the t-statistic for DOF minus 2 rather than DOF and allowing the autocorrelation adjustment to be made at stations where the wind autocorrelation is negative (~44% of the stations used here). The former change makes the testing more consistent with standard t-tests, while the latter prevents a bias between stations.

A reanalysis of the wind data by using the described method yields 57 zonal (u) and 53 meridional (v) wind series as 95% a priori significant out of 165 each (35% and 32%, respectively). The all-station average PEV's are 23.2 (u) and 21.5 (v). In comparison, 1000 series of 24 normally distributed random numbers, simulating the wind, yield 371 series (37.1%) as 95% a priori significant. The fictitious data are found to have an average PEV of 18. The two sets of results are very similar, despite the fact that the fictitious winds are completely nonphysical and therefore contain no solar cycle signal.

A great deal of significance was attached to the spatial PEV patterns in NB. In the present study, alternative PEV patterns are generated by using fictitious solar fluxes which have 'solar cycle' periods other than 11 years. These series are composed of a sine wave and normally distributed random noise. Our purpose here is to model statistically the variability of the real solar flux in a simple manner, realizing that the observed solar flux is the resultant of several waves that change amplitude and period and an apparently random noise component. A critical factor is the ratio of sine wave amplitude to noise standard deviation. (In the course of this study it has been found that increasing the relative amount of noise in the solar flux increases the number of significant stations and the all-station average PEV. This result is a consequence of the particular analytical technique used here and will be discussed later.) An estimate of this ratio is found empirically by comparing correlations of fictitious solar flux and real wind with those of the real solar flux and real wind, where the fictitious solar flux has an 11-year period sine wave with a maximum in 1946. The greatest resemblance between the two sets of correlations occurs when the ratio of amplitude to noise in the fictitious data is 4:1; the numbers of significant stations are 57 (u) and 56 (v) of 165, and the PEV patterns are quite similar (Figures 1a and 1b; v winds only). The correlation coefficients between the real and fictitious solar flux PEV values at all stations are 0.92 (u) and 0.94 (v), indicating a high degree of similarity. The lags at which PEV values are largest show similar spatial coherence but different patterns (Figures 1c and 1d). The change in lag pattern is an effect of the sequence of noise added to the sine wave. Other sequences of random noise have also been used; the PEV patterns remain very similar to the true solar flux case, while the lag patterns vary markedly. Changes in the phase of the solar sine wave have very minor effects on the PEV distribution.

Differing PEV patterns are now created by substituting sine waves of periods 5, 8, 14, and 17 years for the 11-year period wave. These patterns (Figures 2 and 3) have spatial coherences similar to the real flux results, although the geographic locations of PEV maxima vary. (Only the v-wind results are depicted for the sake of brevity. The u-wind patterns are similar in character.) The numbers of significant stations and all-station average PEV's also closely resemble the true flux findings (Table 1). Thus, there is little evidence for an enhanced signal with a period of ~11 years. The statistical relevance of the meridional structures of wind shown in NB (their Figures 6 and 7) is also doubtful. Since the PEV values are quite similar in magnitude at all the periods, like figures could be generated for a given period by selecting appropriate geographical regions of large PEV. Thus, following the same reasoning as Volland and Schaefer [1979], there are large-scale, random variations in the atmosphere on a wide variety of time scales, and we cannot, on statisti-

cal grounds, attribute the 11-year variability to solar effects at this time. As a further check, if the active sun were enhancing atmospheric variability near periods of 11 years, then spectral peaks at those periods should appear at more stations than for other periods. This is not found, as discussed next.

4. Spectral Analysis

The evidence of the previous section suggests that any solar cycle present in the wind data is relatively small in amplitude. Maximum entropy spectral analysis (MESA) has been successfully applied to similar problems [Currie, 1981] and is used here. In addition to the sensitivity of MESA to weak signals, it is more convenient than conventional spectral methods in the comparison of data sets having different lengths. The MESA algorithm used here is that developed by Marple [1980]; according to Marple, the method avoids the peak splitting and frequency bias inherent to the Burg algorithm. MESA is performed on stations having 13 or more years of data that are continuous but for one allowed missing year (filled by interpolation); 152 stations satisfy these requirements. A maximum autoregression order of 20 was allowed, and the Marple stopping tolerances were fixed at 10^{-2}. These stopping criteria were used in all cases, including those employing fictitious data. A signal present in the wind data is assumed to manifest itself as a local spectral peak. These peaks are accumulated at each spectral frequency from every wind series to create histograms

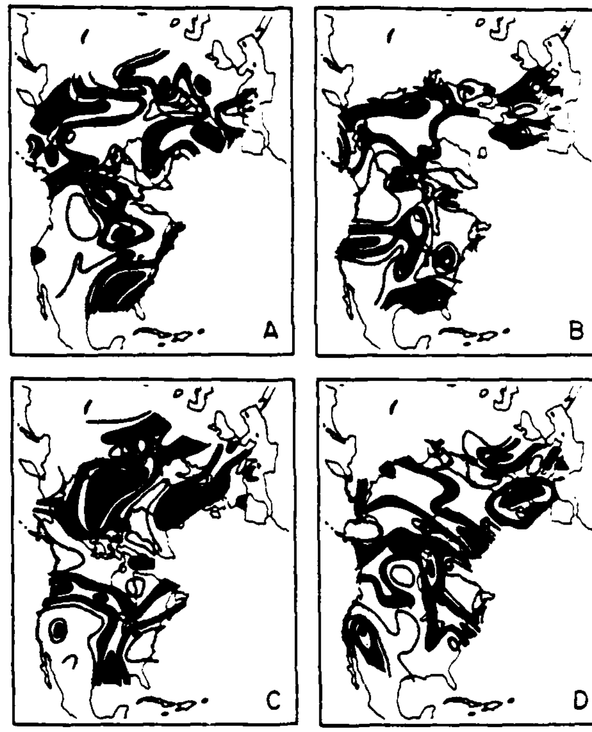

Fig. 3. Lags corresponding to the maximum PEV values between the 300 mbar winter v-wind and fictitious solar fluxes having periods of (a) 5, (b) 8, (c) 14, and (d) 17 years. Lags are depicted as in Figure 1.

(Figure 4). It is evident that neither u- nor v-winds have any appreciable signals near 11-year period. Further MESA studies (as discussed in the next section) have shown that, if an 11-year period signal is present in the wind data, it could appear as having a period of up to 14 years. No significant spectral features are seen at periods between 10.7 and 14 years.

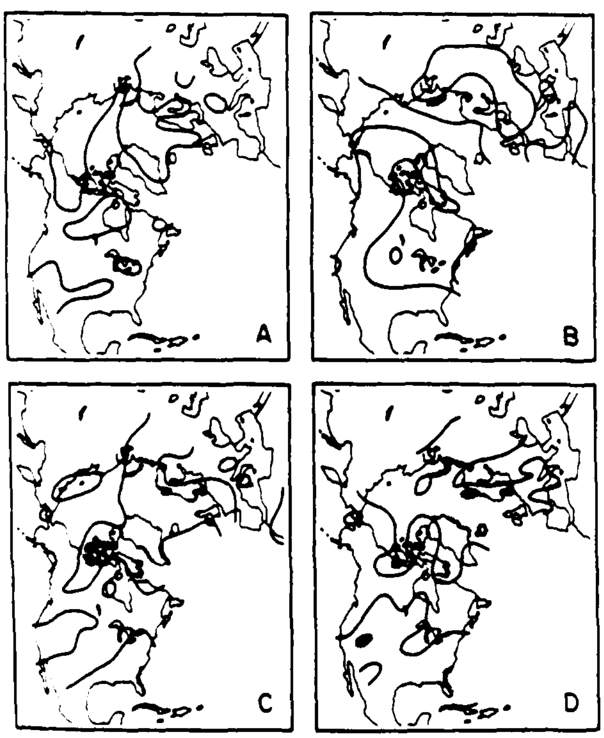

Fig. 2. PEV values between the 300 mbar winter v-wind and fictitious solar fluxes having periods of (a) 5, (b) 8, (c) 14, and (d) 17 years. PEV's are depicted as in Figure 1.

5. Maximum Solar Effect

The results described thus far may be characterized as supporting the null hypothesis (i.e., that no solar cycle influence is present in the data). A second interpretation, in which an influence is taken to exist with an amplitude below that required for detection, suggests that an upper limit on possible solar effects can be obtained by estimating the sensitivity of the analyses. This is done by assuming that solar-induced wind variations have a time dependence similar to that of the solar flux (disregarding an arbitrary time lag). Fictitious wind series of nonzero PEV can therefore be created by adding a fraction of the solar flux to normally distributed random noise. The correlations between these series and the true flux provide the needed sensitivity estimates.

One measure of the data analysis sensitivity can be made by examining the frequency distribution of maximum PEV values. The distribution found by using the u- and v-wind series maximum PEV's from stations of 13 or more years of record (a total of 324 values) can be compared with those calculated from fictitious winds. The

TABLE 1. Analyses of Fictitious and True Solar Flux Data

Fictitious Solar Flux Sine Wave Period (Years)	Number of Stations Found 95% A Priori Significant		Average PEV of All Stations	
	v	u	v	u
5	47	58	17.9	21.7
8	56	55	21.4	20.4
11	56	57	21.1	22.2
14	54	53	20.7	23.2
17	56	51	21.5	24.2
True Flux	57	53	21.5	23.2

The zonal and meridional winds are represented by u and v, respectively.

fictitious wind series are formed by substituting random, normally distributed numbers (variance = 1) for the real wind data. This replacement method produces series which have the same patterns of missing data as the original series. Each real wind series is randomized five times, giving 1620 maximum PEV's. The resulting maximum PEV distributions determined by using the real wind and fictitious wind are quite similar (Figure 5). Next, several sets of 1620 fictitious wind series are generated by adding small portions of the yearly winter mean solar flux to the random, normal series. The sets with added solar fluxes can be expected to have true PEV values equal to 100 times the added solar flux variance, divided by the sum of 1 and the added solar flux variance. The addition of small solar flux portions is seen to produce major changes. It is evident that the distribution from data having 21 PEV is radically different from the true wind result. Chi-square calculations indicate that a best matching of distributions occurs using ~6 PEV fictitious data. The chi-square value changes relatively little between 0 and 6 PEV and increases dramatically between 6 and 12 PEV.

MESA analysis performed on random series of nonzero PEV indicate that a 20 PEV signal is clearly detectable. A 10 PEV signal also is evidenced by a histogram peak, although it is less prominent. The added signal appears in the spectra as having a period between ~10 and 14 years. The displacement of peaks toward longer periods is thought to be a consequence

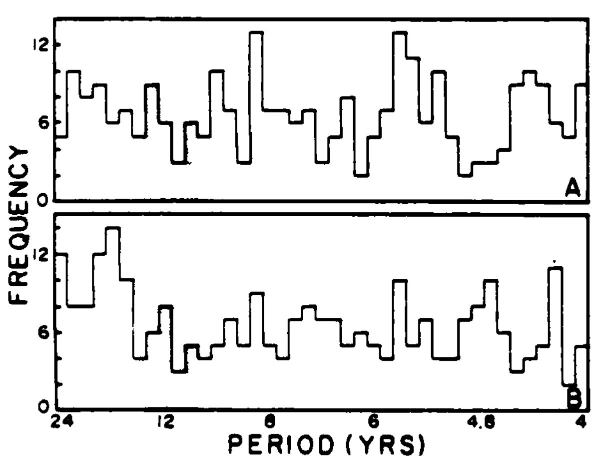

Fig. 4. Maximum entropy spectral peaks, accumulated from all stations, of 300 mbar (a) v- and (b) u-winds. The shaded areas indicate periods between 13.7 and 10.7 years.

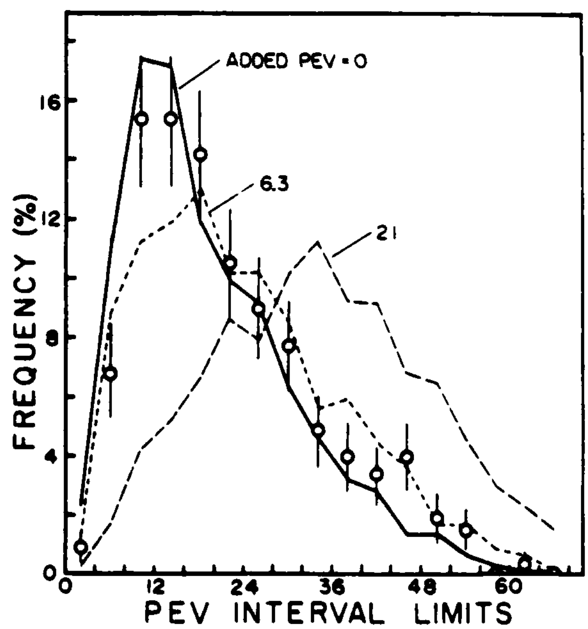

Fig. 5. The frequency distributions (in percent) of maximum PEV's resulting from correlations of the solar flux with real and fictitious winds. The real wind PEV distribution and its approximate 68% confidence limits are denoted by the circles and vertical lines, respectively. The fictitious wind series distributions are denoted by the solid and broken lines. The PEV of each ensemble of fictitious wind series, due to the addition of a fraction of the solar flux, is indicated.

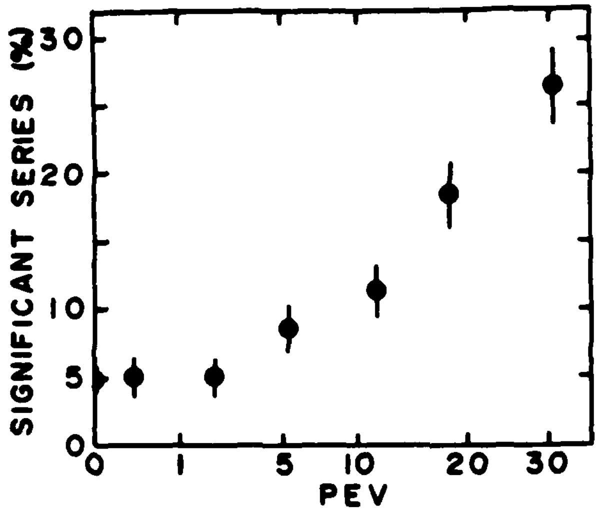

Fig. 6. The percentage of series found to be 95% significant when various fractions of the solar flux series are added. The 95% significance level is found empirically. The PEV of the added solar flux is indicated on the abscissa; the vertical lines indicate the 95% confidence limits.

of the nonuniform data sets. The varying lengths of the data series and their sampling of different portions of the solar flux series may have an effect, and the interpolation of missing data contributes to variance at longer periods.

Another approach to establishing the analysis sensitivity is to examine the percentage of significant stations as a function of PEV. This is done by first determining the *a posteriori* significance level which is exceeded by 5% of the series' maximum PEV's. Three thousand series of random normal noise are analyzed to accomplish this; each series simulates 24 consecutive years of data. This choice of fictitious data ensures that a liberal (i.e., low) significance level is chosen. Different fractions of the annual average solar flux are added to 1000 noisy series and the resulting percentages of significant series are determined using the new level (Figure 6). These show that a 6 PEV signal has a substantially larger number of 95% significant stations than expected from 0 PEV data. A 13 PEV signal is plainly significant. When tested by using the empirically determined significance level, the true winds yield 1.8% and 6.7% of the u- and v-wind stations, respectively, as significant.

These results suggest that the upper limit on a solar cycle influence in the 300 mbar winds is on the order of 6 to 10 PEV. If the ~20 PEV average found in NB were truly related to a physical influence by the sun, it should have been evident in the number of significant stations and the PEV frequency distributions. That no such effects are evident argues against the assumption used in NB that all PEV's can be taken as representing physical coupling of solar and terrestrial variations.

6. Discussion

The results of this study suggest that the 300 mbar winter winds have, at most, 6 to 10% of their variance that can be explained by the solar 11-year cycle. Furthermore, it is difficult to attribute any of the wind variance to solar effects when the statistical significance of the results is considered.

More important is the realization that the large PEV values reported in NB and attributed to solar variations are quite similar to values arising from totally noisy wind data. This similarity is caused by the selection of the largest correlation value from many independent lags. Supposing 41 independent lags to be present, an average of ~2 lags will have correlations that exceed the 95% a priori significance level used in NB. Applying the binominal distribution reveals that ~88% of the series can therefore be expected to be a priori significant. In reality, there are fewer than 41 independent lags; the sinusoidal nature of the solar flux series precludes this. There would appear to be enough, however, to cause serious overestimation of the PEV values and significances. (Note that if the real solar flux formed a pure sine wave, then the analytical method used in NB could have given proper significance levels. The irregular lengths of the wind data series would still have caused inaccuracies, however.) An example given by Panofsky and Brier [1958] gives a clear and concise statement of the problem. The sensitivity of the results to the solar flux signal-to-noise ratio described earlier is evidence of the flaw in a priori multi-lag testing; as the fictitious solar flux sine wave amplitude goes to zero, the percentage of significant stations approaches the large value predicted by the binomial distribution for 41 independent lags.

A final word must concern the insufficiency of the available data. The findings of this study, regarding the absence of statistically significant solar effects, may be anticipated by considering that one or two solar cycles of data can unambiguously reveal only those solar effects that have relatively large magnitudes. The detection of a possible weak solar influence may require additional solar cycles of data or more sophisticated methods of analyzing the data at hand. A theory describing a physical mechanism for solar-terrestrial effects could also be helpful in that it might suggest some way of combining data to enhance possible signals.

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(Received June 14, 1982;
revised March 25, 1983;
accepted April 27, 1983.)

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